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**Research article**

# Energetics and Biomechanics of Uphill, Downhill and Level Running in Highly-Cushioned Carbon Fiber Midsole Plated Shoes

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## Abstract

Road-racing shoes recently experienced major changes. In the recent past, lightweight, thin midsole shoes were thought to help runners maximize their performance. But, in 2017, Nike released the Vaporfly shoe which transformed the thinking about racing shoe design. Incorporating a curved carbon fiber plate embedded in a thick, compliant and resilient midsole resulted in a reduced metabolic cost across a range of running speeds. We hypothesized the new style of shoes would be less effective uphill than downhill due to the larger ground reaction forces and hence greater elastic energy storage in the shoe during downhill running. Eighteen runners completed two days of testing, each comprising two trials of two shoe models (Saucony Endorphin Pro (EP) and Type A) and three grade conditions (uphill, level and downhill), i.e. 12 trials per day. Oxygen uptake, ground reaction forces, and lower-body kinematics were captured during each condition. Comparisons of the percent metabolic benefit were made between shoes for each grade. Stride rate, ground time, peak vertical force, and flight time were regressed with the percent metabolic benefit of the EP over the Type A shoe across grades. Metabolic benefits of the Endorphin Pro were similar across the three grade conditions ($p = 0.778$). No significant correlations were observed between how much benefit one runner got over another specific to grade. The new style of road-racing shoes effectively decreases metabolic cost equally across grades. Differences in running mechanics between runners did not explain greater individual metabolic benefits between shoe conditions during uphill or downhill running.

**Key words:** Marathon, economy, footwear, performance

## Introduction

Recent changes in road-racing shoe construction has prompted research comparing the metabolic benefit of new shoe constructions compared to older styles (Barnes and Kilding, 2019; Hoogkamer et al., 2018; Hoogkamer et al., 2019; Hunter et al., 2019). Various shoe features in these new road racing shoes (such as low foam density, high longitudinal bending stiffness, and a high stack height) may alter metabolic benefit due to changes in kinematics and energy return (Hoogkamer et al., 2018; Hoogkamer et al., 2019; Hunter et al., 2019). All of the aforementioned racing shoe research has been done on level surfaces, preventing direct application to many road races which also include uphill and downhill conditions. However, one recent article found the Nike Vaporfly is not as effective on hilly courses compared with level (Whiting et al., 2021). Kinematic and kinetic differences between uphill and downhill running may affect the magnitude of benefit for this new style of racing shoe.

Changes in surface grade influence running posture, as runners tend to lean forwards with uphill running and backwards with downhill running (Paradisis and Cooke, 2001). Such a change in posture can influence moment arms about lower limb joints and alter mechanical advantage (Roberts and Belliveau, 2005). The longitudinal bending stiffness of a shoe may also lead to changes in mechanical advantage about the ankle due to the center of pressure during toeoff being more anterior, however the increased bending stiffness does not appear to be the reason for improved running economy in this new style of shoe (Healey and Hoogkamer, 2021).

Overall postural changes will also alter foot strike with a shift to midfoot foot strike when running uphill, and to a rearfoot foot strike when running downhill (Gottschall and Kram, 2005). Research on a recently popular racing shoe suggested that the energy savings caused by the shoe may be greater for rearfoot striking than midfoot striking runners (Hoogkamer et al., 2018). This suggests that the benefit of a performance shoe may be greater during downhill running due to the shift to a more rearfoot strike position.

Surface grade may also alter the ground reaction forces experienced by a runner. Downhill running has been found to increase normal impact forces, which is hypothesized to be due in part to the shift to rearfoot strike landing (Gottschall and Kram, 2005; Telhan et al., 2010). These larger forces increase compression and elastic energy storage in the newer shoes that have a greater midsole thickness. It is important to note that results have been mixed on this topic, and with differing downhill grades and speeds used, other studies found no change or a slight decrease in ground reaction forces with downhill running (Snyder et al., 2012; Yokozawa et al., 2004). In uphill running at an equal metabolic effort, runners apply a lower peak normal force (Williams et al., 2020). Runners with a shorter ground time received a greater metabolic benefit associated with the new style of racing shoe (Hunter et al., 2019). This may indicate increased metabolic benefit when running in downhill conditions since running speeds are faster and hence ground contact times shorter during downhill running.

Due to the biomechanical changes associated with downhill running, we hypothesized that new performance racing shoes would have a greater metabolic benefit when running downhill, than with level or uphill running. We also expected certain runners would obtain a greater benefit from the new style of running shoe due to the timing and amount of foam compression that would occur with a vari-

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ety of running techniques. We anticipated differences in stride length, ground time, peak force and flight time would lead to variations in the amount of benefit obtained through wearing the new style of racing shoe at the various grades.

## Methods

Eighteen subjects (10 men and 8 women) ran on two separate days with shoe order reversed. Men were capable of currently running sub-36 minutes for 10,000 m and women sub-40 minutes. On the first visit, they signed an informed consent approved by the university institutional review board. A five-minute warm up at a self-selected pace was completed after 24 retro-reflective markers were placed on the lower body and subjects were fitted with a portable metabolic measurement system (Cosmed K5, Italy) operating in mixing chamber mode (Figure 1). Kinematic and kinetic data were collected and calculated using a 12-camera Vicon Nexus system (Oxford, UK) imaging at 240 Hz and a force-instrumented treadmill (Bertec, Columbus, OH) sampled at 960 Hz. This treadmill is very rigid allowing testing to match overground running more similarly than most. Subjects wore either the control shoe, Saucony Type A (TypeA) or Saucony Endorphin Pro (EP) and ran for 5 minutes each at either uphill, level, or downhill in random order (Table 1 and Figure 2). Then, they switched to the other shoe and ran on specified grades again. A one-minute break was taken in between each five-minute run to either change shoes or adjust treadmill grade. Treadmill speeds were adjusted to produce similar metabolic costs whether running uphill, level, or downhill using a previously created formula (Robergs et al., 1997). The aerobic intensities were relatively low for the caliber of subjects recruited. Men were all capable of currently running sub-36 minutes for 10,000 m and women under 40:00. Subjects had been free from running-related injury for 8 weeks prior to data collection. The second visit included the same methods, but shoe order was reversed.

**Figure 1. The marker set and portable metabolic measurement system.**

Peak ground reaction forces and ground contact times for each step was averaged over a 30-s period and averaged for analysis. The 30-s period provided well over the 25 steps recommended for running mechanics measurements in order to distinguish running technique between people (Oliveira and Pirscoveanu, 2021). Foot strike was recorded for each grade in each shoe was determined was determined from side-view 120 Hz video recordings. Heel strike was classified when the heel of the shoe was first to contact the ground. Midfoot strike was classified as the mid or forefoot contacting first with the heel touching later during ground contact. Forefoot was classified as the mid or forefoot strike contacting first with the heel never touching the ground. Vertical oscillation of estimated center of mass, knee angle at touchdown, maximum knee flexion during swing, maximum hip flexion, and maximum plantar flexion were calculated using a Visual 3d (Germantown, MD) pipeline customized to produce these values. These kinematic data were averaged over a 30-s period during the final minute of each five-minute condition.

**Table 1. Speeds and grades used.**

| Sex | Downhill | Level | Uphill |
|---|---|---|---|
| **Men** | 4.46 m/s @ -4% | 3.83 m/s @ 0% | 3.20 m/s @ 4% |
| **Women** | 4.12 m/s @ -4% | 3.57 m/s @ 0% | 2.86 m/s @ 4% |

**Figure 2. The Saucony Type A (left) and Saucony Endorphin Pro (right) shoes used in this study.**

A median value of oxygen uptake was taken over the final three minutes of each 5-minute run at each grade. Median values were used rather than averages to account for any outliers of individual measurements. Median values for each shoe and grade condition across days were averaged. The percent benefit or drawback to oxygen cost was calculated using these oxygen uptake values relative to the Type A shoe. A linear model was used to determine the effects of shoe and grade on oxygen cost across each grade using the statistical package R (The R Foundation for Statistical Computing, Vienna, Austria).

Stride rate, ground time, peak vertical force, and flight time were correlated with the percent metabolic benefit of the EP over the Type A shoe across the grade conditions. We averaged kinematic, temporal, and kinetic variables along with oxygen cost data across the two days of testing. Oxygen cost savings when changing from the TypeA (control shoe) to the EP (treatment shoe), across all three grade conditions (-4%, 0%, 4%), was calculated as a percentage as follows: Percent Benefit = [(median VO2 in EP) - (median VO2 in TypeA)] / (median VO2 in TypeA).

Because of potential correlations between dependent variables, we used a forward stepwise linear regression model (with Akaike information criterion (AIC) as the selection criteria) to select dependent variables that best explain the variation in percent benefit.

## Results

Contrary to our expectations, the EP did not provide a greater metabolic benefit to during downhill running and a smaller benefit when running uphill compared with level running. Across all three grades, the EP was effective in reducing metabolic cost compared with the TypeA by an average of 1.5% (Type A: 47.4 ± 4.8 ml/kg/min, EP: 46.7 ± 3.8 ml/kg/min, $p = 0.004$). However, the benefit was not different across grade conditions ($p = 0.788$, Figure 3).

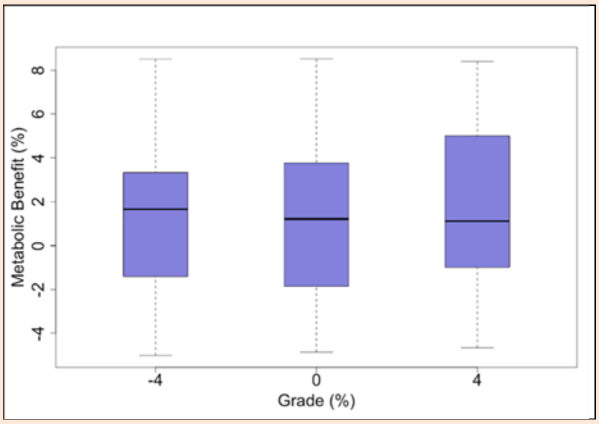


**Figure 3. The percent metabolic benefit of the EP over the Type A shoes used in this study across grades.**

Stride length, ground time, peak vertical force, and flight time were all strongly related with grade. However, to answer our second question, we focused on whether subjects would receive a greater benefit in the EP compared with TypeA across grades due to their running mechanics. The stepwise regression model with the lowest AIC was percent benefit by stride length, but was not significantly different between shoes. Peak vertical force, ground contact time, and flight time were not significant between shoes. This model suggests that grade does not have a significant influence on how much benefit runners receive when changing shoes from the TypeA to the EP at the various grades ($F = 2.45$, Adj $R2 = 0.03$, $p = 0.12$).

Every runner had respiratory exchange ratios well-below 1.0 (mean ± sd = 0.88 ± 0.04) and reported the run as relatively easy providing us assurance that oxygen uptake measures were submaximal and steady-state.

## Discussion

The EP shoe does provide an overall metabolic benefit when compared with the TypeA. On average, across grades, the benefit was 1.5%. This is less of a benefit than previous research showed for other new style road-racing shoes (Barnes and Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2019; Whiting et al., 2021). However, this previous research compared the Nike Vaporfly 4% to either the Nike Zoom Streak or Adidas Adios Boost (Table 2). Our present study that the EP is also effective at decreasing metabolic cost during running when compared with an older style road-racing shoe (Saucony Type A). Our results are also in-line with the a similar uphill/downhill study that investigated the Vaporfly 4% to the Nike Streak 6. Our study varied in the running speeds and attempted to have a similar oxygen cost throughout grades. We also tested whether running mechanics varied due to footwear across grade conditions.

**Table 2. Properties of recently tested shoes.**

| Shoe | Mass (g) | Heel height (mm) |
|---|---|---|
| Saucony Type A | 167 | 17 |
| Saucony Endorphin Pro | 213 | 34 |
| Nike Zoom Streak | 181 | 26 |
| Nike Vaporfly 4% | 186 | 40 |
| Adidas Adios Boost | 198 | 27 |

We anticipated that in the downhill condition, the EP would show a greater metabolic benefit than for the level and uphill conditions. If that had been the case, a redesign of footwear for uphill or downhill courses may have been justified. Efforts can now continue on improvements in footwear with less consideration as to running grades. While the greater forces and shorter ground contact times expected in downhill running matched with the expectation of a greater metabolic benefit from the EP shoe, perhaps the longer strides required for the faster downhill running speed negated any benefit gained from any improvements in energy return.

The added longitudinal bending stiffness was of interest in this study especially for the uphill running condition. During uphill running, foot strike patterns tend to drift towards mid-foot (Gottschall and Kram, 2005; Vernillo et al., 2017). With this shift to mid-foot strike, we anticipated the mechanical advantage about the ankle to be modified due to the location of the resistive force from the center of pressure. This could lead to mid-foot strikers being the more economical uphill running group. There were only six mid-foot strikers in our population, so we did not perform any statistical analyses. However, the means and standard deviations for each group did not show any trend towards one foot strike group being more metabolically advantageous during uphill or downhill running than the other.

Previous research showed that runners receiving a greater metabolic benefit when wearing the new style of shoes spent less time on the ground (Hunter et al., 2019). Our current study checked whether the amount of benefit across grades for a runner was related to their running mechanics, however none of our measured running mechanics significantly predicted how much benefit was provided across grades.

Most major running shoe companies now have a new style of road racing shoe with a thick lightweight midsole and some component like a carbon fiber plate that increases the bending stiffness to the shoe. The results of this study compared two of Saucony's shoes (old and new style), but might not match exactly with other companies' shoes of similar style. However, there are enough similarities in the construction of these shoes across companies, that we expect similar findings were we to include other shoes in these comparisons.

## Conclusion

A similar metabolic benefit was observed when using a new style of road racing shoe across all grades. A priori, we presumed that, during the downhill condition, ground reaction forces and thus midsole compression would be greater which would also store more elastic energy in the shoe midsoles and thus provide oxygen savings. However, we saw no greater oxygen cost savings during the downhill condition. Given the current technology, we suggest that new styles of shoes specific to moderate uphill or downhill running are not necessary. However, extreme grades may provide different results.

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## Key points

- The new style of road racing shoes reduce oxygen cost equally across all grades tested.
- Running mechanics do not predict how much of metabolic cost benefit runners will get across grades.
- Shoe companies do not need to produce grade-specific shoe designs.

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