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A Randomized Crossover Study Investigating the Running Economy of Highly-Trained Male and Female Distance Runners in Marathon Racing Shoes versus Track Spikes

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Abstract

Background Running economy represents a complex interplay of physiological and biomechanical factors that are able to adapt chronically through training, or acutely through other interventions such as changes in footwear. The Nike Vaporfly (NVF) shoe was designed for marathon running on the roads and has been shown to improve running economy by ~4% compared with other marathon shoes, however, during track racing, distance runners traditionally wear a much lighter shoe with an embedded spike plate around the forefoot.

Objective The aim of this study was to determine if, and to what extent, the NVF shoes improve running economy compared with established track spikes (Nike Zoom Matumbo 3 [NZM]) and marathon racing shoes (Adidas Adizero Adios 3 [ADI]).

Methods Twenty-four highly-trained runners (12 male, 12 female) ran 4×5 min trials on a treadmill while wearing each of the four shoe conditions: NVF, NZM, ADI, and the NVF matched in weight to the ADI shoe (NVF+), during three separate visits—visit 1: familiarization; visit 2: 14 and 18 km·h^{-1} for men, 14 and 16 km·h^{-1} for women; visit 3: 16 km·h^{-1} for men, 15 km·h^{-1} for women, plus a maximal rate of oxygen uptake (VO$_2$max) test for both sexes. We measured the rates of oxygen uptake (VO$_2$), carbon dioxide production and biomechanical measures while running at each velocity and shoe condition.

Results The NVF shoe improved running economy by $2.6 \pm 1.3\%$ compared with the NZM, $4.2 \pm 1.2\%$ compared with ADI, and $2.9 \pm 1.3\%$ when matched in weight of the ADI shoe. Among the 24 subjects, the difference in running economy over the four velocities between the NVF and NZM shoes ranged from $+ 0.50$ to $- 5.34\%$, and $- 1.72$ to $- 7.15\%$ for NVF versus ADI. Correlations between changes in running economy and changes in biomechanical variables were either trivial or small, but unclear.

Conclusion The NVF enhanced running economy compared with track spikes and marathon shoes, and should be considered a viable shoe option for track and road racing.

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Key Points

The Nike Vaporfly (NVF) shoe improved running economy by an average of 2.6% compared with track spikes, 4.2% compared with an established marathon racing shoe when unweighted, and 2.9% when matched in weight to the marathon racing shoe.

There appears to be considerable interindividual variation in the amount of energetic saving the NVF shoes provide compared with both track spikes and marathon racing shoes; however, the reasons for such variation have yet to be elucidated.

The NVF shoe lowered rates of oxygen uptake and improved running performance compared with track spikes and marathon shoes, and should be considered a viable shoe option for track and road racing.

1 Introduction

The goal in competitive distance running is to run a given distance in the least amount of time, or at least faster than the next best competitor in slower tactical races. In either case, three physiological attributes contribute to successful distance-running performance: the maximal rate of oxygen uptake (VO_2max); the fractional utilization of aerobic capacity; and the rate of oxygen uptake (VO_2) at a given running velocity (running economy) [1, 2]. It has been reported that running economy can vary by as much as 30% among elite runners with a similar VO_2max [3]. Therefore, a runner with a better running economy (i.e. lower aerobic energy expenditure) can be expected to outperform runners with a higher energy expenditure [4]. Running economy is a multifaceted concept that comprises various metabolic, cardiorespiratory, biomechanical and neuromuscular characteristics during running into a single number [5]. Many of the determining factors of running economy are able to adapt chronically through training, or acutely through other interventions such as changes in footwear [6–8].

On 6 May 2017, Nike, Inc. hosted an event called 'Breaking2' which had the aim of lowering the marathon world record to under 2 h using a combination of science and innovation to help three world-class distance runners reach this goal [9]. A 1:59:59 marathon performance requires an average velocity of 5.86 m·s^{-1} (= 21.1 km·h^{-1}, 2:51 min·km^{-1} or 4:35 min·mile^{-1} pace), which was 0.14 m·s^{-1} or 2.4% faster than the marathon world record of 2:02:57 (5.72 m·s^{-1}) during the time of the Breaking2 event [10]. Since then, the marathon world record has been set at 2:01:39 by Eliud Kipchoge (who participated in the Breaking2 race) at the Berlin

Marathon on 16 September 2018. In addition to an ideal formation of pacers, ad libitum fluids throughout the race, and ideal race climate and race course, Nike also unveiled their new Nike Vaporfly Elite shoe, which combined a new lightweight energy-efficient midsole material with an embedded carbon-fiber plate contributing to increased longitudinal bending stiffness [7, 11–13]. A study examining a prototype version of the Nike Vaporfly shoe showed a 4.01% reduction in energetic cost (running economy) while running at 14, 16, and 18 km·h^{-1} ($p < 0.001$), in 18 highly-trained male runners when shoe mass was matched to another popular elite marathon running shoe, the Adidas Adios Boost (ADI) (Fig. 1) [7]. Now that the commercial version of this shoe is available (the Nike Zoom Vaporfly [NVF] 4%) (Fig. 1), Low et al. replicated the previous study and found energetic cost to be

Fig. 1 The three racing shoe models used in this study. **a** The NVF midsole comprises ZoomX foam made with polyether block amide, an embedded carbon-fiber plate, 31 mm heel height, and 21 mm forefoot height; **b** ADI midsole comprises BOOST foam made with thermoplastic polyurethane, 23 mm heel height, and 13 mm forefoot height; **c** NZM midsole comprises Cushlon foam made with ethylene-vinyl acetate, and a plastic horseshoe spike plate with four 6.35 mm stainless steel spikes. As a fourth shoe condition, we also added 30–35 g of lead weights to the NVF (NVF+) to equalize to the greater mass of the ADI shoes to examine the confounding effects of shoe mass on the energetic cost of running. *NVF* Nike Zoom Vaporfly 4%, *ADI* Adidas Adios BOOST 3, *NZM* Nike Zoom Matumbo 3

2.8% lower than the ADI shoe at 16 km·h^{-1} in 19 subjects ($p < 0.001$) [11], however the shoes were not matched for mass. While the changes in biomechanics explained ~ 20% and 16% of the energetic differences, respectively, Hoogkamer et al. suggested the mechanical properties of the Vaporfly shoes provided the best explanation for the metabolic energy savings [7].

Although the NVF shoe was designed for marathon running on the roads, some athletes choose to wear a similar racing shoe during track racing, where traditionally a much lighter shoe with an embedded spike plate on the bottom mid-fore foot is worn. An examination of the foot-strike patterns at the 2017 USA Track and Field 10-km Championship shows that several elite male and female athletes appear to be wearing prototype versions of the Nike Vaporfly shoe on the track despite the additional weight of the shoe compared with that of a traditional track spike [14]. If indeed the NVF shoe decreases the energetic cost of running by several percent, it would make sense that these shoes could be utilized during both road and distance track racing. Therefore, the purpose of this study was to determine if, and to what extent, the NVF shoes reduce the energetic cost of running (i.e. improve running economy) compared with established track spikes and marathon racing shoes. We compared the energetics and biomechanical characteristics of running in the NVF 4% with those of traditional track spikes, the Nike Zoom Matumbo 3 (NZM), and the successor of the shoes used to run the former official marathon world record, the Adidas Adios BOOST 3 (Fig. 1). Additionally, we translated any potential improvements in running economy to improvements in running performance using the hypothetical model described by Hoogkamer et al. [10] and based on data from Tam et al. [15].

2 Methods

2.1 Subjects

Twenty-four highly-trained runners [5] with a men's shoe size of between US 6.5 and 12 completed the testing protocol (Table 1). All participants had run a 5- and/or 10-km race under 15 or 30 min (men), respectively, or under 17:15 or 35:30 min (women), or an equivalent performance in a different distance-running event of between 3000 m and 25 km. The study was approved by Grand Valley State University's Human Research Review Committee (reference number 18-021-H-GVSU) and was performed in accordance with the standards of ethics outlined in the Declaration of Helsinki. All participants provided written informed consent to participate.

2.2 Experimental Protocol

The study comprised of three visits for each participant. Visit 1 established that subjects were able to run below their lactate threshold at 14, 16, and 18 km·h^{-1} for men, and 14, 15, and 16 km·h^{-1} for women, by measuring blood lactate concentrations ([La]) [16]. During visits 2 and 3, VO$_2$, biomechanical stride characteristics, and blood lactate concentration at 14, 16, and 18 km·h^{-1} for men, and 14, 15, and 16 km·h^{-1} for women, were measured while wearing each of the four shoe conditions—NVF, ADI, NZM, and NVF +. Subjects were asked to replicate their diet, sleep, and training pattern before all laboratory visits.

2.2.1 Shoe Conditions

We compared the commercially available NVF 4% racing shoe (205 g for size US 10) with traditional marathon racing shoes, the Adidas Adios BOOST 3 (ADI; 236 g for size US 10), and traditional track spikes, the NZM (118 g for size US 10) (Fig. 1). We also added 30–35 g of lead weights to the NVF 4% (NVF+) to equalize to the greater mass of the ADI shoes to examine the confounding effects of shoe mass on the energetic cost of running [8, 17] in our fourth shoe condition. However, at the smaller shoe sizes in our study (sizes US 6.5–7), we found the discrepancy in mass between the NVF and ADI shoe was greater (~ 35 g) compared with larger sizes (~ 10 g at size US 12). Therefore, we also had to add 20–25 g of lead weights to the ADI size US 11–12 shoes, such that the relative difference in mass between NVF shoes was 15% of ADI shoes across all shoe sizes. Lead weights ranging between ~ 1 and 4 g were dispersed across the laces of each shoe to not affect the mechanics or comfort of the shoe while running. No weights were added to any sizes of NZM spikes. Subjects were fitted to each shoe

Table 1 Subject characteristics and personal bests at 5000 and 10,000 meters (mean ± standard deviation)

	Age (years)	Height (cm)	Body mass (kg)	Body fat (%)	VO$_2$peak (ml·kg^{-1}·min^{-1})	5-km PB (min)	10-km PB (min)
Male ($n=12$)	24.3 ± 4.5	177.8 ± 7.0	66.5 ± 8.5	5.7 ± 2.1	74.5 ± 4.8	14.35 ± 0.38 ($n=10$)	29.50 ± 0.20 ($n=6$)
Female ($n=12$)	23.0 ± 3.1	165.8 ± 2.9	53.6 ± 4.4	15.6 ± 2.7	62.1 ± 3.5	16.64 ± 0.51 ($n=12$)	34.93 ± 0.41 ($n=7$)

PB personal best, *VO$_2$peak* maximal aerobic power

condition between sizes US 6.5 and 12 based on comfort. Total running use for any pair of shoes did not exceed 40 km.

2.2.2 Visit 1

Initially, subjects had their height, weight and body composition assessed using a bioelectrical impedance analysis scale (Tanita TBF-310; Tanita Corporation, Arlington Heights, IL, USA). Subsequently, subjects wore their own shoes during a 15-min warm-up at the subjects' own self-selected running speed ≤ 14 km·h^{-1} prior to running 3×5-min bouts at 14, 16, and 18 km·h^{-1} for men, and 14, 15, and 16 km·h^{-1} for women, on a level Woodway ELG treadmill (Woodway USA, Waukesha, WI, USA). Subjects took a 5-min break between bouts. A handheld digital tachometer (Shimpo DT-107A; Electromatic Equipment Inc., Cedarhurst, NY, USA) was used to verify all treadmill velocities. To allow familiarization, subjects breathed through an expired-gas analysis system (True One 2400; Parvo Medics, Salt Lake City, UT, USA) during this visit. Within 1 min after the completion of each 5-min trial, we obtained a finger-prick blood sample for blood [La] determination in duplicate (YSI 2300 lactate analyzer; YSI Incorporated, Yellow Springs, OH, USA).

2.2.3 Visits 2 and 3

Visits 2 and 3 were completed in random order, with at least 72 h between visits. Prior to their warm-up, subjects had their height, weight, and body composition reassessed. Subjects began running with a 15-min warm-up at their own selected speed ≤ 14 km·h^{-1}, in their own shoes. Following the warm-up, all subjects completed 4×5-min bouts at 14 km·h^{-1} on a flat Woodway ELG treadmill (Woodway USA) while wearing each of the shoe conditions in a randomized order. In-between bouts, subjects took an ~3-min break while they changed shoes. Note that runners mechanically adapt their biomechanics very quickly in response to changes in surface stiffness [18]. Subsequently, subjects completed another 4×5-min trial at 18 km·h^{-1} for men and 16 km·h^{-1} for women, as previously described. Throughout the running test, heart rate (Polar H7; Polar Electro, Kempele, Finland) was recorded at 5-s intervals and expired gases were continuously measured to determine VO$_2$, carbon dioxide production (VCO$_2$), minute ventilation (V_E), and respiratory exchange ratio (RER). The mean VO$_2$ determined during the last 2 min of each running stage was expressed as running economy (ml·kg^{-1}·min^{-1}), gross oxygen cost of transport (O$_2$COT; ml·kg^{-1}·km^{-1}), and energetic cost (W·kg^{-1}) using the Peronnet and Massicotte equation [19, 20]. In our laboratory, the typical error of measurement [21] of submaximal VO$_2$ was 1.9%. Rating of perceived exertion (RPE) was determined using a 1–10 Borg RPE scale upon

completion of each interval [22]. Blood [La] was assessed at the completion of each running velocity interval series.

Biomechanical measures (stride rate, stride length, contact time, and flight time) were determined using high-speed video analysis (240 frames·s^{-1}) while running at each velocity and shoe condition [23]. The average of each biomechanical parameter during the final 30-s of each running speed and shoe condition was used for analysis. We also used the video recordings to determine the foot-strike patterns of the runners during all trials (rearfoot strike vs. mid/forefoot strike). However, only 5 of the 24 subjects qualified as mid/forefoot strikers, therefore our sample did not permit an evaluation of foot-strike pattern interaction on the energetic cost differences between shoes.

During visit 3, subjects completed the same protocols as visit 2, except they completed a single 4×5-min interval series, this time at 16 km·h^{-1} for men and 15 km·h^{-1} for women, wearing each shoe. After an ~5-min break, the subjects completed a maximal aerobic power (VO$_2$peak) test at the same running velocity, in their own shoes. Treadmill gradient was increased by 1% each minute until volitional exhaustion. The VO$_2$peak was defined as the highest 30-s mean value obtained during the test.

2.3 Statistics

The effects of shoe condition on running economy and biomechanical measures was analyzed using a spreadsheet for post-only crossovers [24]. The value of the ADI shoe for each dependent variable was included as a covariate to improve precision of the estimate of the effects. Effects were estimated in percent units via log transformation, and uncertainty in the estimate was expressed as 90% confidence limits (CLs). The effect size (ES), which represents the magnitude of the difference between the two conditions in terms of standard deviation (SD), was calculated from the log-transformed data by dividing the change in the mean by the average SD of the two conditions. The threshold values for the magnitudes of effects on all measures for small, moderate, large, very large, and extremely large effects were 0.2, 0.6, 1.2, 2.0, and 4.0, respectively, of the between-subject SD in the control condition [25].

To analyze potential relationships underlying the effect of shoes on aerobic energy expenditure, changes in aerobic energy expenditure were plotted against changes in mechanism variables, and the scatterplots were inspected for any linear trend. Resulting correlation coefficients were converted into 90% CLs using a spreadsheet [26]. The contribution of each of the changes in biomechanical measures to the change in aerobic energy expenditure was investigated by using the change scores of each log-transformed measure as a covariate in the spreadsheet for the analysis of the effect of the shoe condition. The change in aerobic

energy expenditure associated with the measure was given by evaluating the effect on aerobic energy expenditure of a difference in the covariate equal to the mean change in the measure, while the change in aerobic energy expenditure independent of the measure was given by adjusting the effect of the treatment to zero change in the measure [25]. To investigate the extent to which one mechanism variable explained the contribution of each other measure, each biomechanical measure was included as an additional covariate in separate analyses. These multiple linear regressions could not be performed with the post-only crossover spreadsheet but were realized instead using the Linest function in Excel (Microsoft Corporation, Redmond, WA, USA).

To estimate how much of an improvement in distance-running performance would be predicted from a reduction in the energetic cost of running in NVF compared with NZM shoes, we used the curvilinear relationship between running velocity and aerobic energy expenditure recently described by Hoogkamer et al. [10] and based on data from Tam et al. [15], with velocity (V) in m·s^{-1}:

$$VO_2(ml \cdot kg^{-1} \cdot min^{-1}) = 5.7 + 9.8158 \times V + 0.0537 \times V^3.$$

To analyze the effects of actual improvement in racing performance in the NVF shoes (in terms of running velocity) compared with baseline performance in the subject's own racing spikes, a spreadsheet for post-only crossovers [24] was used for analysis. Effects were estimated in percent units via log transformation, and uncertainty in the estimate was expressed as 90% CLs.

3 Results

The running economy, O$_2$COT, and energetic cost data for each of the four shoe models at all four running velocities are presented in Table 2. The NVF shoe improved running economy by $4.2 \pm 1.2\%$, on average, across all running speeds compared with ADI, and $2.6 \pm 1.3\%$ compared with NZM. When weighted to match the mass of ADI, the NVF+ was still, on average, $2.9 \pm 1.3\%$ more efficient than ADI across all running speeds. Notably, all subjects were more efficient in NVF than ADI, and only two subjects were more efficient in NZM than NVF (only at the fastest running velocities) (Fig. 2). Among the 24 subjects, the difference in running economy over the four velocities between the NVF and ADI shoes ranged from -1.72 to -7.15% and from $+0.50$ to -5.34% for NVF versus NZM, indicating considerable interindividual variation in the amount of energetic saving the NVF shoes provided. Percent change scores and effects for differences between shoe models at each of the four running velocities is presented in Table 3. There were small to moderate differences between all shoe types at 14 and 16 km·h^{-1}, trivial to small differences at 15 km·h^{-1}, and

moderate to large differences at 18 km·h^{-1} (all $p \leq 0.008$). Differences in heart rate between shoe conditions were trivial (ES < 0.13, $p > 0.31$).

Differences in running economy between men and women are presented in Table 4. There were trivial to small differences between men and women at 14 km·h^{-1} (ES = 0.11–0.38) and 16 km·h^{-1} (ES = 0.17–0.50). All RER values remained below 0.9 for all trials, and [La] values while running 18 km·h^{-1} for men ([La] = 2.6 ± 0.7 mmol·L^{-1}) and 16 km·h^{-1} for women ([La] = 3.3 ± 0.5 mmol·L^{-1}) remained at an intensity below the onset of blood lactate accumulation (OBLA), which specifies an [La] of 4 mmol·L^{-1} [16].

While running in the NVF shoes, subjects generally ran with longer contact time and flight times, slower stride rate, and a longer stride length than the NZM (Table 5). There were no differences in any biomechanical measures between the NVF and NVF + shoes (ES < 0.17, $p > 0.23$); all other effects between shoes were trivial to small. Contact times were 2.5% ($p = 0.02$), 1.6% ($p = 0.09$), and 1.2% ($p = 0.22$) longer in NVF shoes than the NZM shoes at 14, 16, at 18 km·h^{-1} for men, respectively. In the ADI shoes, contact times were 0.2, 0.9, and 0.8% longer compared with the NVF shoes ($p \geq 0.17$) at 14, 16, at 18 km·h^{-1}, respectively. For women, contact times between NVF and NZM shoes were not different at 14 and 15 km·h^{-1} ($p > 0.9$), but 0.76% shorter at 16 km·h^{-1} ($p = 0.36$) and 1.8% slower in the ADI shoes compared with the NVF shoes at all speeds (all $p < 0.05$). Contact times decreased with running velocity at the faster running velocities in all shoes (all $p < 0.01$) (Table 5).

There were no significant differences in stride rate between NVF and ADI ($p > 0.57$) at any running velocities. Stride rate was also not different between NVF and NZM at 14 km·h^{-1} for men ($p > 0.70$), but was 1.1 and 1.2% slower ($p \leq 0.07$) in the NVF shoes compared with the NZM shoes at 16 and 18 km·h^{-1}, respectively. Stride rate for females was 0.9, 1.7, and 1.0% slower ($p \leq 0.08$) in NVF compared with NZM, and 1.4, 1.7, 1.0% slower ($p \leq 0.04$) in the ADI shoes compared with the NZM shoes at 14, 15, and 16 km·h^{-1}, respectively. In men, the NVF shoe was associated with a 0.7% increase in stride length at 14 km·h^{-1} ($p = 0.54$), but no difference was observed at 16 or 18 km·h^{-1} ($p \geq 0.88$) when compared with ADI, whereas differences in stride length were trivial between NVF and NZM shoes at 14 km·h^{-1} (0.2%, $p = 0.67$) and small at 16 or 18 km·h^{-1} (1.3 and 1.2%, respectively; $p < 0.05$). In females, stride length was 1.0% shorter in the NVF shoes compared with the ADI shoes at 14 km·h^{-1} ($p = 0.10$), but not different at 15 or 16 km·h^{-1} ($p \geq 0.85$), whereas, compared with the NZM shoe, the NVF shoe was 0.5% ($p = 0.19$), 1.3% ($p = 0.002$), and 1.7% ($p = 0.001$) longer at 14, 15, and 16 km·h^{-1}, respectively. Stride rate and stride length increased at the faster running velocities in all shoes (all $p < 0.05$) (Table 5).

Table 2 Rates of VO_2, O_2COT, and energetic cost for each of the four shoe conditions at three running velocities for men and women during level treadmill running

	14 km·h⁻¹								15 km·h⁻¹			
	NZM		ADI		NVF+		NVF		NZM	ADI	NVF+	NVF
	Men	Women	Men	Women	Men	Women	Men	Women	Women	Women	Women	Women
VO_2 (ml·kg⁻¹·min⁻¹)	44.72±2.24	43.96±2.70	45.43±2.21	44.44±2.41	44.06±1.99	43.18±2.54	43.38±2.21	42.55±2.58	47.76±3.19	48.42±3.07	47.14±3.01	46.61±3.09
O_2COT (ml·kg⁻¹·km⁻¹)	191.7±9.6	188.4±11.6	194.7±9.5	190.5±10.3	188.8±8.5	185.1±10.9	185.9±9.5	182.4±11.0	191.1±12.8	194.7±12.3	188.6±12.1	186.4±12.4
Energetic cost (W·kg⁻¹)	15.71±0.76	15.46±0.92	15.85±0.71	15.54±0.95	15.50±0.63	15.21±0.95	15.25±0.71	15.01±0.91	16.86±1.13	17.05±1.06	16.67±1.06	16.55±1.03

	16 km·h⁻¹								18 km·h⁻¹			
	NZM		ADI		NVF+		NVF		NZM	ADI	NVF+	NVF
	Men	Women	Men	Women	Men	Women	Men	Women	Women	Women	Women	Women
VO_2 (ml·kg⁻¹·min⁻¹)	52.44±2.14	52.32±2.39	53.61±2.20	53.33±2.35	51.85±2.19	51.95±2.31	51.26±2.23	51.26±2.27	60.49±1.64	61.35±1.12	59.69±1.30	58.88±1.31
O_2COT (ml·kg⁻¹·km⁻¹)	196.7±8.0	196.2±9.0	201.0±8.2	200.0±8.8	194.6±8.1	195.8±8.7	192.2±8.4	192.2±8.5	201.6±5.5	204.5±3.7	199.0±4.3	196.3±4.4
Energetic cost (W·kg⁻¹)	18.39±0.87	18.60±0.85	18.81±0.91	18.88±0.86	18.15±0.91	18.43±0.80	17.99±0.88	18.24±0.82	21.49±1.36	21.74±1.19	21.14±1.21	20.86±1.30

Data are expressed as mean ± standard deviation

NZM Nike Zoom Matumbo 3, *ADI* Adidas Adios BOOST 3, *NVF* Nike Zoom Vaporfly, *NVF+* Nike Zoom Vaporfly plus weight to match of the ADI, VO_2 oxygen uptake, O_2COT oxygen cost of transport
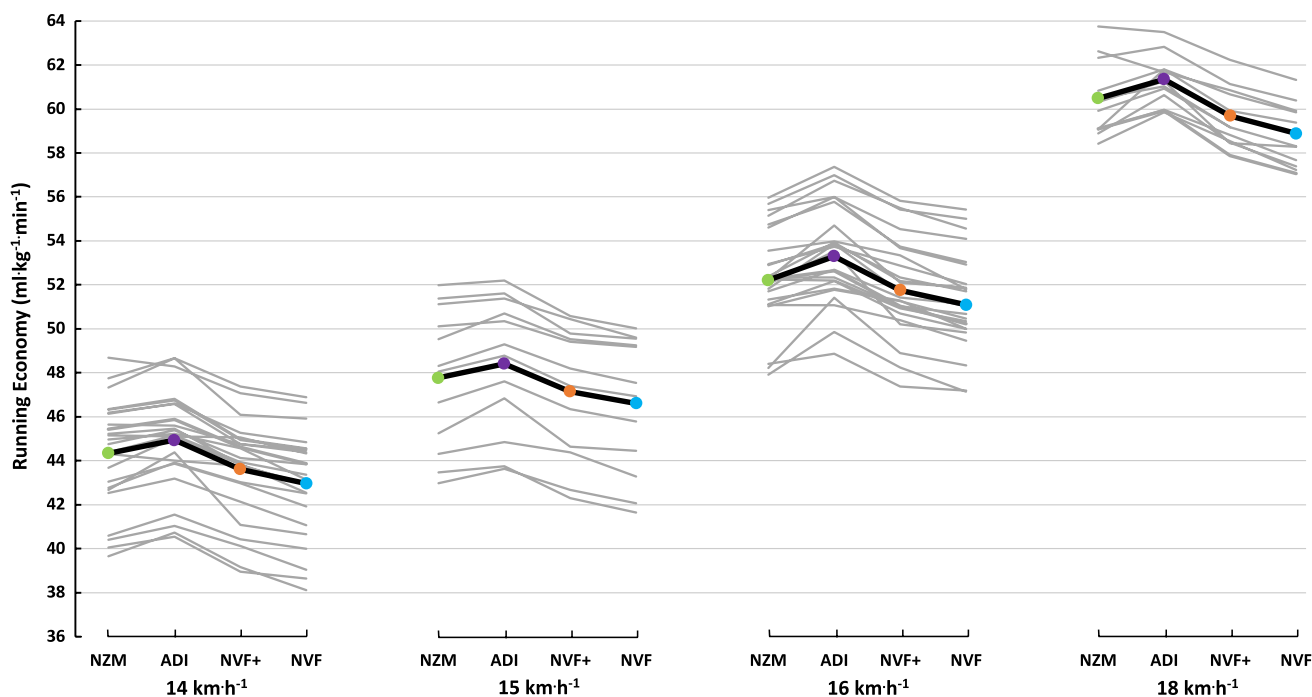
Fig. 2 Rates of VO$_2$ at 14, 15, 16, and 18 km·h^{-1} in each of the four shoe conditions: Nike Zoom Matumbo 3 (NZM), Adidas Adios BOOST 3 (ADI), Nike Zoom Vaporfly 4% (NVF), and NVF plus weight to match the mass of ADI shoe condition (NVF+). Over the four testing velocities, runners in the NVF shoes had 4.2% better running economy (lower VO$_2$) compared with ADI and 2.6% compared with NZM (both $p < 0.008$). When weighted to match the mass of ADI, the NVF+ was 2.9% more efficient than ADI across all running speeds ($p < 0.001$). *VO$_2$* oxygen uptake, *NZM* Nike Zoom Matumbo 3, *ADI* Adidas Adios BOOST 3, *NVF* Nike Zoom Vaporfly 4%, *NVF +* NVF plus weight to match the mass of the ADI shoe condition

There was a moderate correlation ($r = 0.45$, 90% CL − 0.07 to 0.77) between the difference in rates of VO$_2$ and differences in contact time between NVF and ADI shoes at 15 km·h^{-1}. All other correlations between changes in VO$_2$ and changes in biomechanical variables were either trivial or small, but unclear. Using the multilinear regression model for the change scores in aerobic energy expenditure, and change scores in biomechanical variables, we determined, together, the percent changes in contact time, stride rate, and stride length explained 0.95% (±90% CL, ±0.83%) of the average 4.20% reduction in energetic cost between NVF and ADI shoes, while those same biomechanical variables only explained 0.17% (±0.53%) of the average 2.60% reduction between the NVF and NZM shoes.

4 Discussion

The aim of this study was to determine the magnitude of difference in the energetic cost of running between the NVF shoes and that of the ADI marathon racing shoes and NZM track spikes. The main findings indicate that NVF improved running economy by 4.2% compared with ADI, and 2.6% compared with NZM. While our results are comparable to those reported by Hoogkamer et al. [7] and Low et al. [11]

in regard to the differences between the NVF and ADI shoes, no study has examined the difference between the NVF and a track spike. Hoogkamer et al. [7] found an ~4% reduction in energetic cost when running at 14, 16, at 18 km·h^{-1} in a prototype version of the Nike Vaporfly shoe compared with the ADI shoe. In their study, Hoogkamer added 51 g of lead weights to the Vaporfly shoe to equalize to the greater mass of the ADI shoe. They suggested that unweighted Vaporfly shoes would likely save an average of ~4.4% versus the ADI shoes [7], assuming a conservative 0.8% savings per 100 g of shoe mass [8, 27]. Using a similar methodology, Low et al. [11] found metabolic cost to be 2.8% lower in the same Nike Vaporfly shoe (unweighted) we used compared with ADI at 16 km·h^{-1}. Here, when matched by shoe weight, rates of VO$_2$ in the NVF+ shoe were 2.9% less than ADI across all testing speeds. However, the Hoogkamer et al. [7] and Low et al. [11] studies were performed on force-measuring treadmills, which have rigid platforms compared with the Woodway ELG treadmill we used. Previous research has shown that treadmill platform compliance—the amount of compression that occurs when loaded with a certain force—itself affects running economy [28–30]. A less compliant (stiffer) treadmill platform elicits higher oxygen consumption (impaired running economy) [28, 29]. The difference between our study and the other studies [7, 11] might be

Table 3 Percentage change scores (mean ± 90% confidence limits) and effects for differences in rates of oxygen uptake (ml·kg^{-1}·min^{-1}) between shoe models at four running velocities

| | 14 km·h^{-1} ($n=24$) | | | 15 km·h^{-1} ($n=12$) | | |
	ADI	NZM	NVF +	ADI	NZM	NVF +
NZM	− 1.35 ± 0.42% ES = 0.24 $p < 0.001$			− 1.36 ± 0.50% ES = 0.19 $p < 0.001$		
NVF +	− 2.93 ± 0.54% ES = 0.53 $p < 0.001$	− 1.60 ± 0.47% ES = 0.29 $p < 0.001$		− 2.63 ± 0.51% ES = 0.38 $p < 0.001$	− 1.28 ± 0.58% ES = 0.18 $p = 0.002$	
NVF	− 4.40 ± 0.52% ES = 0.80 $p < 0.001$	− 3.10 ± 0.41% ES = 0.56 $p < 0.001$	− 1.52 ± 0.30% ES = 0.27 $p < 0.001$	− 3.75 ± 0.40% ES = 0.54 $p < 0.001$	− 2.42 ± 0.56% ES = 0.35 $p < 0.001$	− 1.15 ± 0.32% ES = 0.16 $p < 0.001$
	16 km.h^{-1} ($n=24$)			18 km.h^{-1} ($n=12$)		
NZM	− 2.04 ± 0.54% ES = 0.47 $p < 0.001$			− 1.43 ± 0.79% ES = 0.66 $p = 0.008$		
NVF+	− 2.90 ± 0.45% ES = 0.68 $p < 0.001$	− 0.91 ± 0.47% ES = 0.21 $p = 0.003$		− 2.71 ± 0.49% ES = 1.26 $p < 0.001$	− 1.30 ± 0.71% ES = 0.60 $p = 0.007$	
NVF	− 4.14 ± 0.40% ES = 0.97 $p < 0.001$	− 2.17 ± 0.48% ES = 0.49 $p < 0.001$	− 1.28 ± 0.24% ES = 0.29 $p < 0.001$	− 4.03 ± 0.39% ES = 1.88 $p < 0.001$	− 2.64 ± 0.66% ES = 1.22 $p < 0.001$	− 1.35 ± 0.29% ES = 0.62 $p < 0.001$

Data are expressed as differences between column and row shoe models (e.g. running at 14 km·h^{-1} in the NZM used − 1.35 ± 1.19% less oxygen [better running economy] than the ADI)

ES effect size, *NZM* Nike Zoom Matumbo 3, *ADI* Adidas Adizero Adios 3, *NVF* Nike Zoom Vaporfly, *NVF +* Nike Zoom Vaporfly plus weight to match of the ADI

Table 4 Percentage change scores (mean ± 90% confidence limits) between shoe models and effects for differences in the rates of oxygen uptake (ml·kg^{-1}·min^{-1}) at 14 and 16 km·h^{-1} between men and women

	Men (%)	Women (%)	Effect size
14 km·h^{-1}			
ADI vs. NVF	4.63 ± 1.26	4.38 ± 1.70	0.19
NZM vs. NVF	3.24 ± 1.01	3.05 ± 1.37	0.13
NVF + vs. NVF	1.59 ± 0.86	1.48 ± 0.89	0.12
ADI vs. NZM	1.58 ± 1.12	1.13 ± 1.25	0.38
ADI vs. NVF +	3.04 ± 1.25	2.90 ± 1.84	0.11
NZM vs. NVF +	1.46 ± 1.47	1.77 ± 1.24	0.20
16 km·h^{-1}			
ADI vs. NVF	4.49 ± 1.29	3.97 ± 0.96	0.37
NZM vs. NVF	2.29 ± 1.35	2.04 ± 1.44	0.17
NVF + vs. NVF	1.16 ± 0.55	1.34 ± 0.79	0.30
ADI vs. NZM	2.20 ± 1.27	1.93 ± 1.83	0.19
ADI vs. NVF +	3.33 ± 1.29	2.64 ± 1.21	0.50
NZM vs. NVF +	1.13 ± 1.36	0.70 ± 1.37	0.29

ADI Adidas Adizero Adios 3, *NVF* Nike Zoom Vaporfly, *NZM* Nike Zoom Matumbo 3, *NVF +* Nike Zoom Vaporfly plus weight to match of ADI

related to the higher compliance of the Woodway treadmill. Furthermore, subjects in the Low et al. [11] study complained of slipping on the treadmill surface when wearing the Vaporfly shoes, which have a relatively smooth outsole compared with ADI or NZM.

Lighter running shoes reduce the energetic cost of running [17, 27, 31], likely due to the reduced inertia for leg swing [5]. Frederick et al. [27] systematically added mass to shoes and found that the rate of oxygen consumption increased by ~1% for each 100 g of weight added to each shoe. Subsequent studies have confirmed the 1% rule at running velocities up to 3.5 m·s^{-1} (12.6 km·h^{-1}) [8, 17]. Specifically, Franz et al. [17] found rates of oxygen consumption to increase by 1.19% per 100 g of added weight to shoes, while the effect was 0.92% per 100 g when running barefoot at 3.35 m·s^{-1} (12.1 km·h^{-1}). Similarly, Hoogkamer et al. [8] found VO$_2$ to be 1.11% higher for each 100 g of weight added to each shoe while running at 3.5 m·s^{-1} (12.6 km·h^{-1}), however the change in performance time over 3000 m was only impaired by 0.78% per 100 g of added mass to shoes. At testing velocities similar to that of the Hoogkamer et al. [8] 3000 m time trial (4.88 m·s^{-1} = 17.6 km·h^{-1}), Frederick et al. [27] suggested that adding 100 g per shoe had a < 1% effect (0.75%) on rates of oxygen consumption. While not a direct comparison due to differences in shoe design, in

Table 5 Biomechanical measures for each of the four shoe conditions at three running velocities for men and women

| | 14 km·h⁻¹ | | | | | | | | 15 km·h⁻¹ (Women) | | | |
	NZM		ADI		NVF +		NVF		NZM	ADI	NVF +	NVF
	Men	Women	Men	Women	Men	Women	Men	Women				
Contact time (ms)	221±17	230±40	227±17	234±40	227±16	231±42	227±17	230±42	220±36	222±35	220±42	221±40
Flight time (ms)	121±25	114±18	117±26	114±18	120±23	117±21	119±24	115±18	117±20	117±20	123±19	123±20
Stride rate (strides.min⁻¹)	87.5±5.0	88.4±9.5	87.5±5.3	87.4±9.8	87.5±4.9	87.4±9.2	87.7±4.7	87.6±9.2	90.4±8.5	89.4±8.0	88.4±9.2	88.3±9.6
Stride length (m)	2.69±0.16	2.51±0.13	2.68±0.16	2.53±0.12	2.70±0.15	2.53±0.14	2.69±0.15	2.52±0.13	2.66±0.12	2.72±0.13	2.70±0.13	2.70±0.13

| | 16 km·h⁻¹ | | | | | | | | 18 km·h⁻¹ (Men) | | | |
	NZM		ADI		NVF +		NVF		NZM	ADI	NVF +	NVF
	Men	Women	Men	Women	Men	Women	Men	Women				
Contact time (ms)	205±16	213±40	212±20	215±36	209±18	211±38	209±17	211±39	194±16	198±17	197±15	197±14
Flight time (ms)	126±22	124±19	120±22	123±18	125±22	127±18	126±22	127±20	125±17	125±19	127±17	127±18
Stride rate (strides.min⁻¹)	90.8±4.8	90.8±10.4	89.8±5.1	90.0±9.8	89.5±4.8	89.9±9.7	89.8±4.7	90.0±10.2	94.2±4.8	93.0±4.1	93.0±4.0	93.0±3.8
Stride length (m)	2.96±0.16	2.83±0.11	2.97±0.15	2.85±0.11	3.00±0.16	2.86±0.11	3.00±0.16	2.87±0.11	3.19±0.16	3.23±0.15	3.23±0.14	3.23±0.14

NZM Nike Zoom Matumbo 3, *ADI* Adidas Adizero Adios 3, *NVF* Nike Zoom Vaporfly, *NVF+* Nike Zoom Vaporfly plus weight to match of the ADI

our study the NZM spike shoe weighed ~100 g (50%) less than the ADI shoe, and rates of VO_2 were 1.4% lower in the NZM. Interestingly, the NZM spike shoe weighed ~58% of the NVF shoe (difference 70–100 g less), and VO_2 was, on average, 2.6% less in the NVF shoe, indicating that properties of shoes other than mass can be substantially influential. Similarly, despite only a 30–35 g difference between the NVF and NVF + shoe conditions, rates of VO_2 were ~1.2–1.5% different across all running speeds, which is an important consideration when comparing our results with those of Hoogkamer et al. [7], where the NVF + and ADI shoes would be the closest shoe conditions for comparison in our study (Table 3).

Hoogkamer et al. [7] suggest the midsole properties of the Nike Vaporfly shoes provide the best explanation for the metabolic energy savings. In addition to weight, shoe cushioning and longitudinal bending stiffness have each been shown to affect the energetic cost of running [32, 33]. Virtually all running shoes have midsoles made from various foam materials that, to varying degrees, cushion impact, and store and return mechanical energy. The amount of energy stored by a foam material depends on its compliance, whereas the percentage of stored mechanical energy that is returned is called resilience [34]. Mechanical testing of the prototype version of the Nike Vaporfly and ADI shoes revealed that the Vaporfly shoe was two-times more compliant than the Adidas Adios Boost 2 shoe, deforming 11.9 mm versus 5.9 mm, and more resilient than the Adidas Adios Boost 2 shoe, returning 87.0% of the potential energy compared with 75.9% [7]. Taken together, the Nike Vaporfly shoes can return more than double the mechanical energy per step of the ADI shoes (7.46 J vs. 3.56 J, respectively) [7]. For perspective, Ker et al. [35] calculated that the Achilles tendon and arch of the human foot return approximately 35 and 17 J of stored energy, respectively, while running at 4.5 m·s⁻¹ (16.2 km·h⁻¹) [35]. Some energy must also be stored and released in other tendons and ligaments of the legs. However, unlike shoes, the energy stored in a tendon depends on the forces (muscles) that stretch the tendon, which require metabolic energy (adenosine triphosphate [ATP]) [5]. Running shoes with compliant and resilient midsoles may actually lower the ATP cost of muscular contraction for the same force production and thus reduce the rate of oxygen demand at any given speed. Generally speaking, male runners in our study elicited greater improvement in running economy compared with female runners while wearing the NVF shoes (Table 4), which could be related to the compliance and resilience of the shoes. One would presume that the heavier male runners would have elicited greater ground reaction forces compared with the lighter female runners (Table 1) at any given running speed, resulting in higher mechanical energy storage in the midsole. Assuming the same percentage of stored mechanical

energy is returned (resilience), the shoes could return more mechanical energy for the heavier male runners than for the lighter female runners, potentially resulting in a reduction in VO_2 rates.

The midsole of the NVF shoe also includes a relatively stiff carbon-fiber plate inside the thick responsive foam midsole (Fig. 1), thereby increasing longitudinal bending stiffness. These shoe properties change the mechanical advantage of the foot and leg by facilitating bringing the center of pressure from under the heal or middle portion of the foot during the contact period to the toes, leading to a greater moment-arm from the ankle [36]. Previous research has shown such plates can reduce the rate of oxygen demand (improve running economy) by ~ 1% [32] and improve sprinting performance [37]. The relationship between running economy and the amount of longitudinal bending stiffness in the midsole of a shoe has been described as a 'U-shaped' curve [32], suggesting there is an optimal amount of longitudinal bending stiffness to improve running economy, which is primarily dependent on athlete mass [32]. Similar results were found when investigating the influence of midsole longitudinal bending stiffness on running performance [37].

To our knowledge, this is the first study to compare the Nike Vaporfly marathon shoe with a spike shoe traditionally worn during track racing. With regard to shoe type, materials and structure, the NZM spike would be considered a lightweight racing shoe featuring a thin Cushlon foam midsole with a flexible horseshoe-shaped plastic plate and four pin spikes around the forefoot (Fig. 1). Running barefoot or in racing spikes that have a flat midsole with little to no cushioning can cause runners to make acute, short-term changes in running gait from a rearfoot strike to a forefoot strike, increase cadence, and reduce vertical oscillation of the center of mass, which might contribute to improved running economy [38, 39]. Indeed, in our study, subjects did have a faster cadence and shorter ground contact times while wearing the NZM spikes compared with that of other shoe models (Table 5). However, running in shoes with minimal or no cushion also requires significant muscular effort to cushion the impact of the foot with the ground [40]. Conversely, when running in cushioned shoes, the midsole material performs the task of cushioning, presumably with less muscular effort; however, all cushioning materials have mass, which in itself incurs a metabolic cost [10]. Frederick et al. [40] found that running barefoot and while wearing well-cushioned shoes with a mass of 290 g, each required the same rate of oxygen consumption. Similarly, Tung et al. [30] showed that running barefoot on 10 mm of surface cushioning improved running economy by 1.63% compared with barefoot running on a rigid running surface. These same subjects also ran in medium-weight shoes (230 g each) with ~ 10 mm of foam midsole cushioning, and the metabolic cost of running in those shoes was the same as running barefoot on the rigid surface [30]. Thus, the two factors appeared to counteract each other. Barefoot or minimalist shoe running involves little to no added mass but requires metabolic energy for cushioning. Running in cushioned shoes requires more energy for accelerating the shoe mass but provides the cushioning, with a reduced metabolic cost [10].

While running in the NVF shoes, subjects generally ran with longer contact times and stride lengths, and consequently slower stride rates, compared with NZM spike shoes (Table 5). Relative to the ADI shoes, contact times were generally shorter, stride lengths slightly longer, and differences in stride rate were trivial while wearing the NVF shoes. These changes are in opposition to Hoogkamer et al. [7], who found contact times to be slightly longer and stride rate slower in a prototype version of the Nike Vaporfly shoe compared with the ADI shoe. Furthermore, Gonzalez et al. [13] that found no difference in contact times and longer stride lengths. Some of these discrepancies might again be related to differences in treadmill compliance and slipperiness discussed previously. Furthermore, in the current study, biomechanical parameters were based on high-speed video recordings versus force treadmill data in others [7, 12, 13]. Neither of these studies measured changes in the NVF shoe compared with a racing spike shoe. However, we agree with previous studies that the trivial to small biomechanical changes are not enough to explain the small to large reductions in rates of VO_2 [7, 11–13]. Indeed, similar to other studies [7, 12, 13], changes in biomechanical characteristics (i.e. contact time, stride rate, and stride length) only explained a small amount of the variance in the changes in rates of VO_2. Although the biomechanical characteristics measured in this study and previous studies showed little explanation for the changes in running economy [7, 11–13], other kinematic and kinetic factors such as angular velocities of limb segments and joints, and ground reaction forces, have also demonstrated a relationship with running economy [5]. Ferris et al. [18] suggested that runners adjust the stiffness of their stance leg when running on compliant surfaces by reducing knee flexion during the stance phase. This adjustment allows runners to maintain similar center of mass movement (e.g. contact time and stride rate) regardless of surface stiffness [18], while also improving the mechanical advantage of the muscles acting around the joints, which reduces the energetic cost of body-weight support [28]. We did not measure joint kinematics in the present study, however Gonzalez et al. [13] observed no change in knee flexion and an increase in center of mass vertical oscillation in the NVF shoe that is consistent with the greater stride lengths observed among the subjects in our study wearing the NVF shoe. Furthermore, in previous studies, vertical ground reaction forces measured while wearing the NVF shoe have been inconsistent with the higher, lower, and no

differences observed compared with the ADI shoe [7, 12, 13]. This suggests a variety of individual characteristics, such as biomechanics, physiology, and psychology (i.e. comfort), may all be contributing factors to the improvements in running economy while wearing the NVF shoes [32, 37].

Although we did not directly set out to evaluate the effects the energetic saving of different racing shoes would have on running performance, nine of the participants (four male, five female) in this study had competed in 3 or 5 km races in their own racing shoes (spikes for all nine aforementioned participants) before participating in this study, and then again over the same respective distance in NVF shoes. All performances were competed on a 300-m indoor track within 3 weeks of testing and are considered all-out time-trial performances for qualifying purposes. It is important to note that there was no control group that also ran at both times in the same shoes for comparison, nor was there any way of blinding the subjects to shoe conditions. Furthermore, it would be expected that runners get faster over a 6-week period, therefore the improvements in performance reported here cannot all be attributed to differences in shoes. The curvilinear relationship that exists between energetic cost and running velocity, due in part to air resistance [10], would suggest that the 2.60% reduction in rates of VO_2 between the NVF and NZM shoes should translate into a $2.27 \pm 0.07\%$ increase in running velocity according to the model based on overground running data in top-level Kenyan marathon runners by Tam et al. [15]. However, in our subsample of nine runners, their actual improvement in racing performance in terms of running velocity was $1.90 \pm 0.42\%$. This subsample of runners included seven National Collegiate Athletic Association (NCAA) Division 2 National Track and Field Championship qualifiers (five All-American [which means they finished in the Top 8 in the Nation at their respective distances], one national champion, and two national runner-ups, all in the NVF shoes), of which three males ran under 14 min and four females ran under 17 min for 5 km, in the NVF shoes. An unpublished study from the *New York Times* using 495,000 public marathon and half marathon race reports, and shoe records from the Strava fitness app, suggests the Vaporfly shoes account for a ~ 4.1% (95% confidence interval 1.1%) improvement in race time, compared with a previous result when switching to the NVF shoes [41]. However, track racing is different than road racing, given that approximately half of the time running on a track is devoted to turning. For an object to turn (on a flat track) while moving at a set velocity, it needs a centripetal force. When running, this centripetal force is generated from the mediolateral friction beneath the foot. Given the high stack height (31 mm heel height and 21 mm forefoot height) (Fig. 1) and presumably less traction of the NVF shoe compared with the NZM spike, it could be explored that the NVF may actually be underperforming during track racing due to more instability and greater frictional forces needed to turn, however studies of this nature have not yet been performed.

5 Conclusions

Wearing NVF shoes during level submaximal treadmill running resulted in substantial improvements in running economy compared with traditional track spikes (NZM) and marathon racing shoes (ADI) in male and female well-trained distance runners. Substantial differences were also observed, albeit lower in magnitude, when the NVF shoes were weight-matched to that of the ADI shoes, indicative that factors other than shoe mass are influential on running economy. Importantly, the enhanced running economy translated into worthwhile improvements in running performance measured theoretically and with real competition data.

Compliance with Ethical Standards

Ethical Approval This study was performed in accordance with the ethical standards of the Declaration of Helsinki. Ethics approval was obtained from the Grand Valley State University Institutional Review Board (protocol number 18-021-H-GVSU).

Informed Consent Informed consent was obtained from all individual participants included in this study.

Conflict of interest Kyle R. Barnes and Andrew E. Kilding declare that they have no conflicts of interest relevant to the content of this article.

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