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Original article

Metabolic cost of level, uphill, and downhill running in highly cushioned shoes with carbon-fiber plates

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Abstract

Background: Compared to conventional racing shoes, Nike Vaporfly 4% running shoes reduce the metabolic cost of level treadmill running by 4%. The reduction is attributed to their lightweight, highly compliant, and resilient midsole foam and a midsole-embedded curved carbon-fiber plate. We investigated whether these shoes also could reduce the metabolic cost of moderate uphill (+3˚) and downhill (−3˚) grades. We tested the null hypothesis that, compared to conventional racing shoes, highly cushioned shoes with carbon-fiber plates would impart the same ∼4% metabolic power (W/kg) savings during uphill and downhill running as they do during level running.
Methods: After familiarization, 16 competitive male runners performed six 5-min trials (2 shoes × 3 grades) in 2 Nike marathon racing-shoe models (Streak 6 and Vaporfly 4%) on a level, uphill (+3˚), and downhill (−3˚) treadmill at 13 km/h (3.61 m/s). We measured submaximal oxygen uptake and carbon dioxide production during Minutes 4−5 and calculated metabolic power (W/kg) for each shoe model and grade combination.
Results: Compared to the conventional shoes (Streak 6), the metabolic power in the Vaporfly 4% shoes was 3.83% (level), 2.82% (uphill), and 2.70% (downhill) less (all $p < 0.001$). The percent of change in metabolic power for uphill running was less compared to level running ($p = 0.04$; effect size (ES) = 0.561) but was not statistically different between downhill and level running ($p = 0.17$; ES = 0.356).
Conclusion: On a running course with uphill and downhill sections, the metabolic savings and hence performance enhancement provided by Vaporfly 4% shoes would likely be slightly less overall, compared to the savings on a perfectly level race course.

Keywords: Energetics; Incline; Locomotion; Oxygen consumption; Running economy

1. Introduction

Since the introduction of the Nike Vaporfly 4% (VF4) shoes in 2017, elite marathon races have been dominated by athletes using these shoes and similar models.[1−3] Today, almost all running brands have their own marathon racing shoes that, like the Vaporfly, combine a resilient foam with a stiff curved plate. The 4% in the Vaporfly name originates from laboratory measurements showing that the shoes reduce the metabolic energy consumption during running by an average of ∼4% as compared to conventional road-racing shoes.[4] Subsequent studies have confirmed and extended the original study findings.[5−7] All 4 laboratory studies were performed on level treadmills or tracks.[4−7] However, the world is not flat, and many marathon courses have significant uphill and downhill sections. Here, we investigated whether the VF4 shoes could provide similar metabolic benefits during uphill and downhill running.

The metabolic cost of level running is dominated by the cost of generating force to support body mass,[8−10] but during uphill running there is an additional cost of raising body mass against gravity.[11,12] With the net work done against gravity and less braking,[13] the role of elastic energy storage and recovery is smaller in uphill running.[14,15] Therefore, mechanical energy storage and return in the compliant and resilient Vaporfly midsoles, which is substantial during level running,[4] might be expected to be less and to have a smaller effect on overall metabolic cost during uphill running. Furthermore, greater longitudinal bending stiffness of the midsole might increase ankle moments.[16−18] That was not the case for VF4 shoes during level running, likely because of the plate curvature and

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midsole geometry,[19,20] but it is unknown how ankle moments and angular velocities are affected by increased longitudinal bending stiffness during uphill/downhill running.

Downhill running at a constant velocity requires net mechanical energy dissipation rather than elastic storage and return,[14,15] so greater midsole foam resilience might actually be disadvantageous. However, during downhill running at 3° in conventional shoes, the normal impact force peak is 18% greater than during level running.[13] The hypothesis concerning the metabolic cost of cushioning [21,22] posits that shock attenuation requires extra muscular effort and, hence, metabolic energy. Accordingly, the greater compliance and midsole thickness of the VF4 shoes[4] would be expected to reduce impact and, hence, metabolic cost. Overall, it is unclear *a priori* whether shoes with more resilient and compliant midsole foam properties are metabolically advantageous *vs.* traditional footwear during uphill/downhill running.

Based on prior research that concerned the VF4 shoes for level running, we anticipated that metabolic power (W/kg) would be 4% lower in the VF4 compared to traditional marathon racing flats. However, given the uncertainty about uphill/downhill running, we tested the overall null hypothesis that the metabolic percent savings of the VF4 shoes *vs.* the traditional marathon racing shoes for uphill and downhill running would be the same as for level running. To test this hypothesis, 16 competitive male runners successfully completed level, uphill (+3°, ∼+5%), and downhill (−3°, ∼ −5%) treadmill running trials in the traditional marathon racing shoes and the VF4 shoes while we measured their metabolic power consumption.

2. Methods

2.1. Human subjects

We present data for 16 healthy, male, competitive runners (age = 27.4 ± 5.4 years, mass = 66.5 ± 4.0 kg, and height = 178.8 ± 4.9 cm; mean ± SD) who volunteered and provided written informed consent as per the University of Colorado Institutional Review Board (Protocol #19-0221) and in accordance with the Declaration of Helsinki. All subjects wore either size US9.5 or US10 shoes and had run a sub-35 min 10-km race, sub-1:20 h half-marathon race, or equivalent performance in a different distance-running event within 12 months prior to their test date. All subjects were acclimated to the local altitude (1655 m). We tested only male subjects because of the need for subjects to fit into the available shoe sizes and the need for an adequate aerobic capacity to run submaximally at the uphill test speed.

2.2. Shoe conditions

We compared the VF4 (Nike, Beaverton, OR, USA) to the Nike Streak 6 (S6; Nike). The VF4 has a thick midsole composed of a compliant and resilient foam (ZoomX foam made with polyether block amide) with an embedded curved carbon-fiber plate. The S6 is a traditional marathon racing shoe with a thinner midsole composed of ethylene-vinyl acetate and a rearfoot air-cushioning unit. Prior to the introduction of the VF4, many elite and recreational marathoners ran in the S6. Images and additional details of both shoe models were provided in Hoogkamer et al.[4] The VF4 and S6 were similar in mass (203 g for VF4 size US9.5, 209 g for VF4 size US10, 196 g for S6 size US9.5, and 198 g for S6 size US10). To minimize any possible deterioration of the cushioning properties, total running use for any pair of shoes did not exceed 50 km.

2.3. Treadmills

Subjects ran on 2 custom-made and identical treadmills: 1 level and 1 mounted on 3° aluminum wedges.[13,23] The level and 3° treadmills had identical motors, flywheels, belt surface material, rigid decks, and size dimensions (running surface 188cm × 50 cm), and they were mounted side-by-side. We chose to study uphill and downhill running at ± 3° (∼± 5%) to emulate the hills encountered during the Boston Marathon, which has the most significant hills of the World Marathon Major courses. We conducted both the uphill and downhill running trials on the ± 3° treadmill by reversing the motor direction as required.

2.4. Experiment protocol

Subjects reported to the laboratory for 2 visits. Visit 1 familiarized subjects with the shoe models and the expired gas-analysis system (True One2400, Parvo Medics, Salt Lake City, UT, USA) and with running on the inclined/declined treadmill. Visit 2 occurred at least 24 h after Visit 1. We instructed the subjects to fast for at least 2 h prior to each visit. Subjects began both Visit 1 and Visit 2 with a 5- to 10-min warm-up run at a self-selected pace (easy/moderate intensity) either on the level treadmill inside or on paved surfaces outside the laboratory. All familiarization and test trials were 5 min in duration, and at least 5 min of rest were allowed between trials. Subjects ran at a speed of 13 km/h (3.61 m/s, 7:26 min/mile) for all trials. We used a hand-held digital tachometer (Shimpo DT-107a; Electromatic Equipment, Cedarhurst, NY, USA) to verify the treadmill velocities. We chose the treadmill speed based on pilot tests indicating that 13 km/h up the 3° incline would be close to the greatest intensity that our subjects could sustain in a steady state, relying on oxidative metabolism.

Subjects wore their own shoes for the warm-up and for the level running trial during Visit 1. They wore each testing shoe model twice during Visit 1 and 3 times during Visit 2. Testing consisted of 5 trials during Visit 1 including 1 trial on the level, 2 trials on the incline, and 2 trials on the decline. Visit 2 was composed of 6 trials including 2 trials on the level, 2 trials on the incline, and 2 trials on the decline. Subjects always ran on the level grade first, but we randomly assigned the shoe model and grade orders. We maintained the trial orders for Visit 1 and Visit 2 for each subject and counterbalanced the shoe-grade orders. The counterbalance plan was for 18 subjects, but due to the coronavirus disease 2019 (COVID-19) pandemic, we were forced to stop data collection at $n = 17$.

During both Visit 1 and Visit 2, we measured the submaximal rates of oxygen uptake ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) using the expired-gas analysis system. During Visit 1, we monitored real-time respiratory exchange ratio (RER) ($RER = \dot{V}CO_2/\dot{V}O_2$) to ensure that subjects were running at a submaximal aerobic intensity ($RER < 1.0$), particularly during the uphill running trials. All subjects ran all Visit 1 trials at an $RER < 1.0$, but 1 subject exceeded 1.0 during the uphill testing trials during Visit 2, so we excluded him from data analysis, leaving $n = 16$. From the data collected during Visit 2, we calculated the average gross metabolic power for the last 2 min of each trial using the Péronnet and Massicotte equation.[24,25] We weighed subjects after each trial and had them drink enough water to match their initial trial weights.

2.5. *Statistical analysis*

Using R-Studio (www.rstudio.com), we compared metabolic power (W/kg) across conditions using a two-way repeated measures analysis of variance (ANOVA) considering 2 factors: grade and shoe model. We assessed for a slow component by statistically comparing (paired *t* tests) the average rate of oxygen uptake during Minute 4 *vs.* Minute 5 for every subject and condition. Additionally, we compared the between-shoe metabolic power percent differences between downhill running and level running as well as between uphill running and level running with paired *t* tests. We calculated effect size as Cohen *d*.[26] Last, we conducted 2 pair-wise regression analyses to evaluate potential correlations between the metabolic power percent differences between shoes during level running *vs.* uphill running and during level running *vs.* downhill running. We used a traditional level of significance ($p < 0.05$).

3. Results

Compared to the S6 shoes, the VF4 shoes required significantly less metabolic power during level, uphill, and downhill treadmill running (all $p < 0.001$) (Fig. 1). On average, the VF4 shoes reduced metabolic power by 3.83% ± 1.89% for level, 2.82% ± 1.39% for uphill, and 2.70% ± 2.49% for downhill running (Figs. 1 and 2). The percent change (VF4 *vs.* S6) in metabolic power for uphill running was significantly less compared to level running ($p = 0.04$; ES = 0.561), but it was not significantly different between downhill and level running ($p = 0.17$; ES = 0.356) (Fig. 2). The VF4 shoes provided metabolic savings for all 16 subjects during level running, for 15 subjects during uphill running, and for 14 subjects during downhill running (Fig. 2). Notably, 3 different individuals experienced metabolic penalties. The metabolic power percent difference between the shoes for individual subjects ranged from 0.10% to 7.24% during level, −0.20% to 5.47% during uphill, and −2.06% to 6.66% during downhill running. We did not find statistically significant linear intrasubject correlations between metabolic savings/penalty for level and uphill running (Fig. 3A), nor between level and downhill running (Fig. 3B). RER remained <0.99 for all trials, and we did not detect a slow component in our recordings of oxygen uptake. Across all conditions, the rate of oxygen uptake during Minute 5 was not statistically different from Minute 4 ($p = 0.193$). Table 1

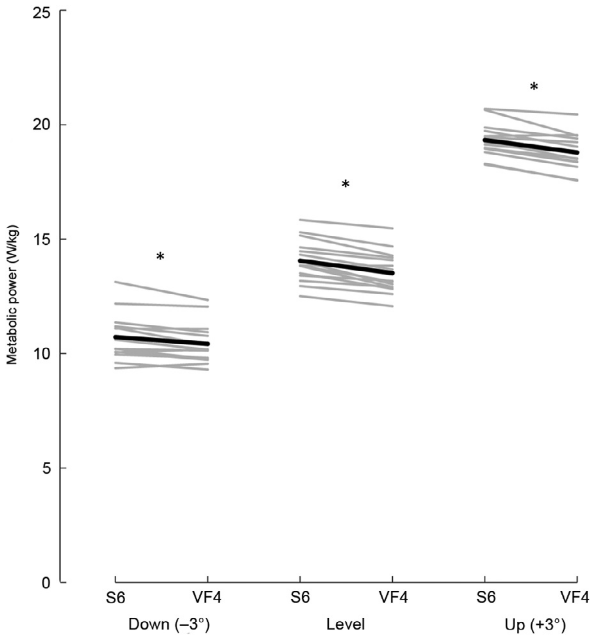

Fig. 1. Gross metabolic power for running in Nike Streak 6 (S6) and Nike Vaporfly 4% (VF4) shoes at 13 km/h on a declined Down (−3°), level (Level), and inclined Up (+3°) treadmill. Mean metabolic powers ($n = 16$) are represented by bold black lines. Gray lines depict individual subjects. Collectively, metabolic power was lower in the VF4 *vs.* the S6 shoes for all 3 grades (* $p < 0.001$).

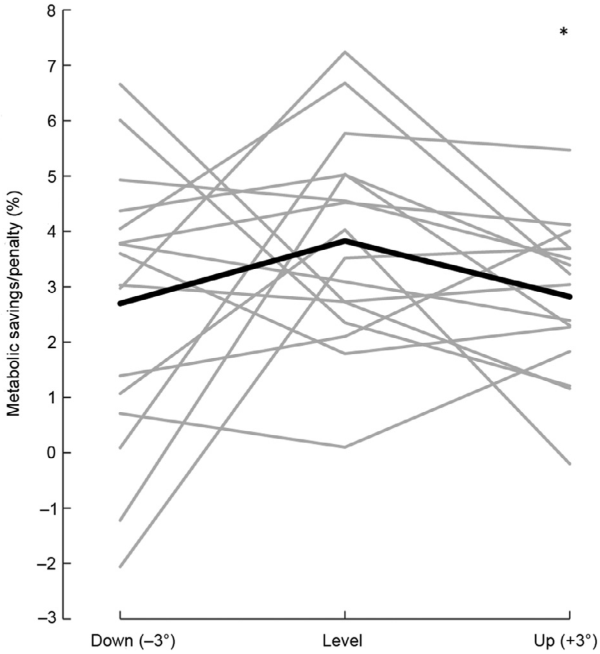

Fig. 2. Percent difference in metabolic power for Nike Vaporfly 4% *vs.* Nike Streak 6 shoes at 13 km/h on a declined Down (−3°), level (Level), and inclined Up (+3°) treadmill. On average ($n = 16$), the VF4 shoes reduced metabolic power by 2.70% ± 2.49% for downhill, 3.83% ± 1.89% for level, and 2.82% ± 1.39% for uphill. Mean metabolic power savings are represented by bold black lines. Gray lines depict individual subjects. * $p < 0.05$, percent savings was less during uphill *vs.* level running.

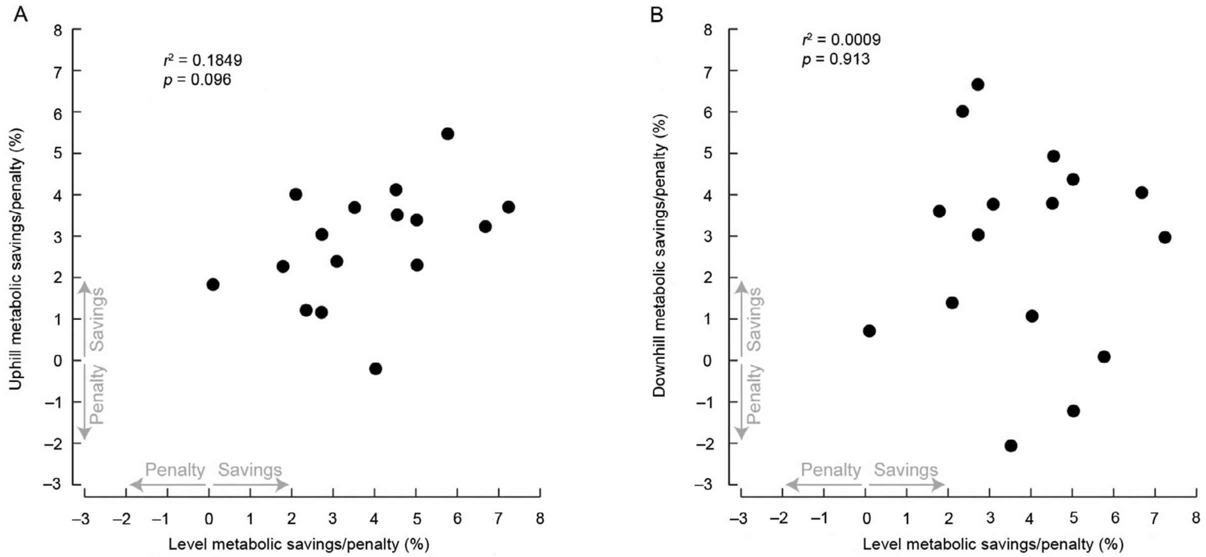

Fig. 3. Comparisons of the metabolic savings/penalties for Nike Vaporfly 4% *vs.* Nike Streak 6 shoes. (A) Running uphill *vs.* on the level and (B) Running downhill *vs.* on the level. Linear regression correlations between metabolic savings/penalty for level and uphill running and between level and downhill running were weak and not significant.

provides data for metabolic power and RER. Although we prefer metabolic power for many reasons,[27,28] we also provide $\dot{V}O_2$, energetic cost of transport, and oxygen cost of transport data for the convenience of the reader.

4. Discussion

In the present study, we investigated the gross metabolic cost differences between the VF4 and S6 shoes during level, uphill (+3°), and downhill (−3°) treadmill running. Our level-running results reconfirm the prior research, which found an ~4% metabolic savings when running in the VF4 shoes as compared to running in the S6 shoes.[4–6] We reject the null hypothesis regarding uphill running because the 2.82% savings during the uphill (+3°) trials was statistically less than the 3.83% savings on the level ($p = 0.04$). We fail to reject the null hypothesis for downhill running. Even though the average VF4 *vs.* S6 difference was numerically less (2.70% savings), the sizable subject−response variability (further discussed below) resulted in a p value of 0.17. Fig. 2 illustrates the greater range of responses during downhill running among our subjects, from 6.66% savings to 2.06% penalty for wearing the VF4 shoes. Overall, we found that during level, uphill, and downhill running, VF4 shoes provide substantial metabolic savings and. thus, presumably a performance advantage.[29,30] Bradshaw et al.[31] recently reported running economy values for a different shoe model (Saucony Endorphin Pro) for level, up, and down a 4% gradient. They found overall smaller (<1.7%) oxygen uptake savings, and the savings were not significantly different between grades. Like the Vaporfly shoes, the Saucony Endorphin Pro shoes also have a curved carbon-fiber plate embedded in a polyether block amide foam midsole, but subtle differences apparently exist between the 2 shoes.

In the present study, the level metabolic savings again averaged ~4%, but we now see that on a marathon course with level, uphill, and downhill sections, the metabolic savings would likely be somewhat less overall. Note that because of the nonlinear relationship between metabolic power and running velocity, the percent time savings is not equivalent to the percent metabolic savings.[30] At the elite level, the conversion is roughly two-thirds, such that a 4% metabolic savings translates to ~2.68% time savings. If a marathon course were exactly one-third level, one-third uphill at

Table 1
Metabolic power, $\dot{V}O_2$, ECOT, and O_2COT for all grades and shoe models (mean ± SD).

	Level		Uphill (+3°)		Downhill (−3°)	
	S6	VF4	S6	VF4	S6	VF4
Metabolic power (W/kg)	14.06 ± 0.89	13.52 ± 0.87	19.33 ± 0.69	18.79 ± 0.75	10.72 ± 0.97	10.42 ± 0.85
RER ($\dot{V}CO_2/\dot{V}O_2$)	0.86 ± 0.03	0.87 ± 0.04	0.92 ± 0.04	0.90 ± 0.03	0.82 ± 0.03	0.82 ± 0.04
$\dot{V}O_2$(mL/kg/min)	40.01 ± 2.48	38.46 ± 2.40	54.35 ± 1.84	52.98 ± 1.99	30.82 ± 2.76	29.96 ± 2.37
O_2COT (mL/kg/km)	184.7 ± 11.4	177.5 ± 11.1	250.9 ± 8.5	244.5 ± 9.2	142.3 ± 12.7	138.3 ± 10.9
ECOT (J/kg/m)	3.89 ± 0.25	3.74 ± 0.24	5.35 ± 0.19	5.20 ± 0.21	2.97 ± 0.23	2.89 ± 0.23

Abbreviations: ECOT = energetic cost of transport; O_2COT = oxygen cost of transport; RER = respiratory exchange ratio; S6 = Nike Streak 6; VF4 = Nike Vaporfly 4%; $\dot{V}O_2$= rate of oxygen uptake.

3°, and one-third downhill at 3°, the expected metabolic savings would be the average of 3.83%, 2.82%, and 2.70%, respectively which equals 3.12%. Applying the two-thirds metabolic savings-to-time savings conversion suggests a 2.08% savings in time over the full course. The actual time savings for 50 elite male marathoners using various versions of the Vaporfly shoes for a variety of Marathon Major courses ranging from the very flat Chicago course to the much hillier and net downhill Boston course was 2.0%.[3]

Perhaps shoe midsole properties could be specifically tuned for various inclines. It may be that an uphill running shoe should have a greater heel-toe differential in height and/or be made with a less compliant midsole material. Conversely, a downhill-specific running shoe midsole might have a thicker forefoot region and be constructed with enhanced energy-dissipating properties. Such specific shoes could be effective for all-uphill or all-downhill races. Alternatively, we can conceive of a running shoe with dynamically adjustable or even automatic modulation of midsole properties.

Our study has some limitations to consider. The metabolic penalty for running in the VF4 shoes, which was exhibited by 3 of our subjects, may be due simply to trial-to-trial variations. We prefer to average replicate trials, but with 3 grade conditions (level/incline/decline) and 2 shoe conditions, replicates would have entailed 12 trials per subject in 1 session, which may have led to fatigue. Although our study had adequate statistical power to resolve differences between the 2 shoe models, we were underpowered to compare the percent of savings between the level and downhill running conditions. A *post hoc* power analysis[26] indicated that we would need to test 81 subjects to obtain $p < 0.05$ with 90% power. Our study focused on male subjects and, thus, may not be exactly applicable to female runners. However, Barnes and Kilding[5] found metabolic savings of a similar percent for both males and females during level treadmill running in VF4 shoes.

Most of our subjects had limited experience with downhill treadmill running, so more habituation might have reduced the variability in the metabolic responses. It seems that some subjects may need to learn to relax and let gravity and the highly-cushioned shoes do their job during downhill running.[32] Our results are limited to a running velocity of 13 km/h; metabolic savings may differ at slower or faster velocities, though that was not the case in previous studies of level running.[4,5] We chose the incline and decline angles to be reasonable and realistic for road racing, but many trail races involve much steeper hills. More extreme angles may be useful for elucidating the mechanisms behind the metabolic savings. Finally, we did not quantify any biomechanical or electromyographic aspects behind the metabolic savings. We encourage future investigators to expand on our study in terms of subjects' sex, running velocities, incline/decline angles, and biomechanical/neuromuscular measurements.

5. Conclusion

We found that compared to conventional racing shoes, the Nike Vaporfly 4% shoes provide significant metabolic savings during level, uphill, and downhill treadmill running. The percent savings are about 1% less during uphill running.

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Authors' contributions

CSW conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, wrote and reviewed drafts of the paper, and approved the final draft; WH conceived and designed the experiments, analyzed the data, prepared figures and/or tables, wrote and reviewed drafts of the paper, and approved the final draft; RK conceived and designed the experiments, wrote and reviewed drafts of the paper, and approved the final draft. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

WH has received research grants from Puma and Saucony; RK is a paid consultant for Nike. Puma, Saucony, and Nike were not involved in the study design, the writing of the manuscript, or the decision to submit it for publication. CSW has no conflicts of interest relevant to the content of this article.

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