

1 **Recent Improvements in Marathon Run Times Are Likely Technological,**
2 **Not Physiological**

3 **Running Title:** Recent running times are likely technological

4
5 Borja Muniz-Pardos¹

6 Shaun Sutehall²

7 Konstantinos Angeloudis³

8 Fergus M. Guppy⁴

9 Andrew Bosch²

10 * Yannis Pitsiladis^{3,5}

11 y.pitsiladis@brighton.ac.uk

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13 1 - GENUUD research group, Faculty of Sport and Health Sciences, Department of Physiatry
14 and Nursing, University of Zaragoza, Zaragoza, Spain

15 2 - Division of Exercise Science and Sports Medicine, University of Cape Town, Cape Town,
16 South Africa

17 3 - Collaborating Centre of Sports Medicine, University of Brighton, Eastbourne, UK

18 4 - Centre for Stress and Age-related Disease, School of Pharmacy and Biomolecular
19 Sciences (PaBS), University of Brighton, Brighton, UK.

20 5 - International Federation of Sports Medicine (FIMS), Lausanne, Switzerland

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25 **Abstract**

26 Every women's and men's world records from 5 km to the marathon has been broken since
27 the introduction of carbon fibre plate (CFP) shoes in 2016. This step-wise increase in
28 performance coincides with recent advancements in shoe technology that increase the
29 elastic properties of the shoe thereby reducing the energy cost of running. The latest CFP
30 shoes are acknowledged to increase running economy by more than 4%, corresponding to a
31 greater than 2% improvement in performance/run time. The recently modified rules
32 governing competition shoes for elite athletes, announced by World Athletics, that includes
33 sole thickness must not exceed 40 mm and must not contain more than one rigid embedded
34 plate, appear contrary to the true essence and credibility of sport as access to this
35 performance-defining technology becomes the primary differentiator of sporting
36 performance in elite athletes. This is a particular problem in sports such as athletics where
37 the primary sponsor of the athlete is very often a footwear manufacturing company. The
38 postponement of the 2020 Summer Olympics provides a unique opportunity for reflection
39 by the world of sport and time to commission an independent review to evaluate the impact
40 of technology on the integrity of sporting competition. A potential solution to solve this
41 issue can involve the reduction of the stack height of a shoe to 20 mm. This simple and
42 practical solution would prevent shoe technology from having too large an impact on the
43 energy cost of running and, therefore, determining the performance outcome.

44

45 **Key Points**

- 46 • Recent improvements in marathon world records are unlikely physiological but rather
47 technological, if for no other reason that such a step-wise improvement in
48 physiological attributes underpinning performance are unlikely. On the other hand,
49 there has been such a step improvement in shoe technology.

- 50 • Current shoe designs for road running, and more recently for track running, that
51 include a CFP seem to greatly reduce the energy cost of running and, as a
52 consequence, most long-distance road running records have been broken in the last
53 three years by athletes wearing CFP shoes.
- 54 • Current rules are therefore no longer fit for purpose, requiring revision to safeguard
55 the integrity of sport. A potential solution to solve this issue can involve the
56 reduction of the stack height of a shoe to 20 mm.

57

58 **1. Background**

59 On 12th October 2019, Kenyan athlete Eliud Kipchoge ran 42.2 km in 1:59:40 h:min:sec
60 racing in personalised carbon fibre plate (CFP) shoes (i.e., Nike Alphafly) in an unofficial
61 event in Vienna [1]. The following day, Eliud's compatriot Brigid Kosgei ran 2:14:04 in the
62 Chicago marathon using Nike prototype CFP shoes, breaking Paula Radcliffe's 16 year-old
63 women's marathon record by over a minute [2]. Kosgei's previous personal best times were
64 2:18:35 and 2:18:20 set at the 2018 Chicago and 2019 London marathons, respectively
65 [3,4]. Since the launch of CFP shoes by Nike in 2016, the men's and women's world
66 records in long-distance road running (i.e., from 5 km to the marathon) have all been broken
67 by athletes wearing CFP shoes (Table 1), raising concerns that the introduction of this
68 technology leads to a distinct non-physiological advantage. Notably, the first spikes
69 including a full-length rigid plate within the midsole were introduced by Nike at the 2020
70 Diamond League in Monaco (14th of August 2020), and their impact was immediate [5]. Of
71 the 65 athletes competing in races between 800 and 5 000 m, 50 athletes wore Nike spikes,
72 and 40 of these athletes wore the new spiked shoes [6]. During this event, the 5 000 m male
73 world record was broken by an athlete wearing the new spikes; a record that had stood for
74 16 years [7]. Two months later during a race in Valencia, this same athlete broke 15-year-

75 old world record in the men’s 10 000 m wearing the same spiked shoe (Table 1) [8]. This
76 event in Valencia also saw Ethiopian athlete Letesenbet Gidey break 12-year-old world
77 record in the women’s 5 000 m (Table 1) [8]. This situation has led some athletes to take
78 drastic measures, for example, a well-known Spanish marathoner who holds the third fastest
79 Spanish marathon time: 2:07:27 h:min:sec, chose to break his Adidas contract to use a Nike
80 CFP shoe and subsequently qualified for Tokyo 2020 [9]. In response to the performance
81 advantage experienced by athletes wearing CFP shoes designed by Nike, other companies
82 have reacted by designing their own CFP shoes aiming to provide their athletes with a
83 competitive advantage (shoe models displayed in Table 2).

84

85 [INSERT TABLE 1 HERE]
86

87 [INSERT TABLE 2 HERE]

88

89 **2. Carbon-fibre plate shoes and running performance**

90 While the true impact of CFP shoes on running performance remains to be scientifically
91 tested in the field, there are indications that the recent improvements in long-distance
92 running times are unlikely to be biologically driven. Three main strategies have been
93 proposed to reduce mechanical energy during exercise and therefore increase physical
94 performance: (a) to optimise the musculoskeletal system, (b) to maximise the energy
95 returned, and (c) to minimise the energy loss or absorption [61,62]. Previous studies [63,64]
96 have demonstrated that flexion of the forefoot or metatarsophalangeal joint during running
97 induces greater energy loss, resulting in reduced running and jumping energy costs when
98 increasing the midsole longitudinal bending stiffness of a shoe and reducing the range of
99 motion of the metatarsophalangeal joint. The current shoe technology including both CFP
100 and thick but light midsoles (especially those composed of a polyamide block amide, PEBA

101 [65]) are designed for increased energy return [66,67] mediated by the action of passive
102 elastic recoil, requiring less energy per step [68]. In order to obtain a more detailed image,
103 our group performed a computed tomography scan of the CFP shoe that was used to win the
104 2016 Berlin marathon (shown in Figure 1). The success of CFP shoes is reflected in public
105 race reports and shoe records from the social-fitness network Strava. This network,
106 containing hundreds of thousands marathon performances, shows that CFP shoes provide a
107 3-4% advantage over “traditional” running shoes [69]. Guinness et al. [70] observed in 578
108 elite marathoners (308 males, 270 females) that switching to CFP running shoes resulted in
109 75% of men running 1.5-2.9% faster (from 2 to 4 min) and 71% of women running 0.8-
110 2.4% faster (from 1 to 4 min) during a marathon. These findings are consistent with an
111 observational experiment by our group, in which we determined the effects of wearing CFP
112 shoes (Vaporfly NEXT%) compared with “traditional” race shoes by the same manufacturer
113 on 10 km performance in a semi-elite female athlete in 40+ age category. This athlete ran a
114 total of six 10 km races over similar courses (three wearing a race shoe without a CFP, and
115 three in the Nike NEXT%, in a randomised order) with a minimum of two weeks between
116 races, and maintaining her habitual training load throughout this period. The courses were
117 flat and at sea-level, and the CFP shoe elicited a 2.3% improvement over the “traditional”
118 racing shoe (Mean time: 39:04 min:sec vs. 40:03 min:sec, respectively). Notably, running
119 cadence was identical (195 steps·min⁻¹) but stride length was 5 cm longer in the CFP shoe.

120

121 [INSERT FIGURE 1 AROUND HERE]

122

123 Laboratory studies have reported improvements of approximately 4% in running economy
124 (RE) while exercising in CFP shoes at a submaximal intensity (commonly between 14 and
125 18 km·h⁻¹) during a period of approximately 5 min [66,71,72]. Notably, large inter-

126 individual differences in this important proxy of running performance have also been
127 observed, with some runners experiencing no improvements in RE and others showing up
128 to 6.4% [72]. This wide range of response in RE to CFP shoes seems to depend upon foot
129 strike patterns and the different optimal shoe stiffness for different runners [12]. This inter-
130 individual response to CFP shoes represents a priority area of future research. In our
131 laboratory, the RE of an Olympic and current male world record holder improved by 2.6%
132 when running on a treadmill at $21 \text{ km} \cdot \text{h}^{-1}$ for 3 min while wearing a shoe containing a CFP
133 compared with his previous preferred racing shoe. Notably, this athlete's personal best in
134 the marathon has improved by 2.7% in the 4 years since transitioning to CFP shoes.

135

136 RE is highly influenced by anatomical and biomechanical differences [73], for example an
137 increased lower-limb length due to a greater stack height of a running shoe will enhance RE
138 when body mass is maintained [74]. Although the precise mechanisms are not clear [75],
139 longer and thinner legs seem to contribute to a greater moment of inertia and therefore a
140 reduced muscular demand to move the legs forward [76]. While increasing stride length has
141 been observed to be more efficient than increasing stride frequency by devoting less energy
142 to leg acceleration, longer legs have shown to favour longer stride length and therefore a
143 better RE [76,77]. In addition to improved RE by increasing leg length, a greater stack
144 height provides an increased spring space within the shoe for more elastic energy to be
145 stored and released during every foot-strike. For example, the 8 mm (from 23 to 31 mm)
146 increase in effective leg length of the Vaporfly 4% shoe compared to its predecessor (i.e.,
147 Nike Streak) is thought to explain about 25% improvement provided by the Nike Vaporfly
148 4% [65]. This is based on a biomechanical model (i.e., the LiMb model) linking limb length
149 to cost of transport in terrestrial animals [78,79]. For running, this model derives the rate of
150 muscular force production during running from effective limb length, the excursion angle of

151 the limb during stance phase, and the energy cost of swinging the limb [80]. Although stack
152 height is scaled according to shoe size, this is not linear and provides shorter athletes a
153 disproportionately larger increase in lower leg length, which has been suggested to be a
154 beneficial contributor to RE [75]. The newly released Nike Alphafly offers an additional 8.5
155 mm leg length and spring space (39.5 mm) and can be expected to further enhance RE by
156 more than 4%. The energetic advantage of such CFP shoes is non-physiological and more in
157 line with benefits derived from exoskeletons, blades and prosthetics limbs. While invariably
158 CFP shoes improve running performance, there are no longitudinal studies advocating an
159 increased risk of injury due to a more rigid/stiff sole [81]. However, an experienced
160 marathoner with the second fastest marathon of all time, was forced to withdraw from the
161 2020 London marathon claiming his use of CFP shoes caused him several injuries due to
162 the lack of foot stability [82]. Future research should also focus on the study of injury risk
163 when using CFP shoes by developing standard testing protocols to identify optimal forefoot
164 stiffness and stability depending on competitive level, individual foot strike patterns and
165 running distances. The outcome of this research should also inform the shoe regulations.

166

167 **3. Issues with current regulation**

168 The magnitude of race performance improvements by athletes running in CFP shoes are
169 analogous to those expected from various blood doping substances and methods included
170 on the prohibited list of the World Anti-Doping Agency (WADA), such as erythropoietin,
171 which have been shown to improve performance by 4-6% [83,84]. On 31st January 2020,
172 World Athletics reacted to this controversy in shoe technology by announcing new rules
173 stating that sole thickness of a marathon shoe must not exceed 40 mm (25 mm for spiked
174 shoes) and must be on sale for at least four months before they can be used in competition
175 [85]. Soon after, Nike launched the Alphafly shoe with a 40 mm sole, a CFP insert, and the

176 addition of air pods in the metatarsal region [86]. The close proximity of the Alphafly
177 launch to the new regulation announcement raised concerns that the rules had been drafted
178 to “legitimise” Nike’s CFP shoe series in response to accusations of “technological doping”
179 [87], doing little to protect the principle of fairness in sporting competition. These new rules
180 have resulted in a *footwear arms race* to develop patented CFP inserts by numerous shoe
181 companies (Table 2). This is contrary to another important principle of fairness in sport –
182 *the universality of sport*, where technological developments used by athletes need to be
183 reasonably available to all competitors [85]. The cost of these shoes (shown in Table 2)
184 would limit its availability only to a minority of athletes, being inaccessible for the largest
185 sections of society especially from underdeveloped countries, ironically alienating many
186 East Africans, who have dominated long-distance running worldwide for more than 50
187 years.

188

189 **4. A solution towards equity and fairness in sport**

190 The sudden improvements in performance times witnessed since the emergence of CFP shoes
191 in 2016 seem technologically driven rather than physiological, as recently suggested [88].
192 Joyner et al. recently discussed the different factors potentially explaining the fast marathons
193 witnessed during the last few years [88]. Physiological and training factors in addition to shoe
194 technology and drafting are proposed as the main contributors to recent official and unofficial
195 (i.e., exhibitions in Monza and Vienna) fast marathons. However, the abrupt drop in world
196 records across all distances since the launch of CFP shoes suggest that shoe technology may
197 have a greater role than the other proposed factors (i.e., since 2017, training methods or the
198 physiology of the athletes are unlikely to have produced such fast marathons). Drafting is
199 undoubtedly another factor influencing the energy cost of running, although this strategy has
200 already been employed during official races much earlier than 2017, which suggests drafting

201 could not explain the plethora of world records witnessed during the last three years. The
202 International Olympic Committee recently announced a one-year postponement of the 2020
203 Tokyo Olympics due to the COVID-19 pandemic [89]. This delay provides the opportunity
204 for World Athletics to commission an independent review focusing on technological fairness
205 to systematically evaluate the impact of technology on the essence and integrity of sporting
206 competition. The controversy today surrounding the “legality” and “ethics” of CFP shoes is
207 not unprecedented. In 2009, the International Swimming Federation (FINA) was obliged to
208 modify the rules and ban full-body swimsuits in response to numerous sudden world records
209 broken by swimmers wearing this technology [90]. Similarly, the IAAF (now World
210 Athletics) faced their own technological issue with shoe designs in the 1960s. In the latter
211 case, both the 200 and 400 m world records were broken within the space of two weeks in
212 1968, with both athletes wearing the newly developed “brush” shoe [91]. This shoe contained
213 68 small pins, compared with the traditional four or six spike shoes and appeared to improve
214 grip and stability on a racetrack. The advantage of this technology was later confirmed in a
215 study that reported improvements in running performance in five out of six athletes tested
216 [92]. The breaking of two world records within a short time period led to the banning of this
217 technological advancement by the athletics governing body and the records broken with these
218 shoes sponged from the records [91]. The recent decision to permit the use of CFP shoes
219 throughout the sport of athletics (including track) is contrary to previous decisions of this
220 governing body regarding footwear innovations; a decision that must be urgently and
221 carefully reconsidered. A potential solution to solve this issue can involve the reduction of
222 the stack height of a shoe to 20 mm. This simple and practical solution would prevent shoe
223 technology from having too large an impact on the energy cost of running and, therefore,
224 determining the performance outcome. Companies would be able to innovate within this

225 space, but shoe technology would not be the primary differentiator of sporting performance
226 in elite athletes.

227

228 **Declarations**

229 **Conflicts of interest** One of the authors, YP, is the founding member of the Sub2 project
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232 review.

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241 and edited the manuscript. All authors approved the final version of the manuscript.

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491 Figure 1. Computed tomography scan of the CFP shoe used during the 2016 Berlin marathon.
492 Table 1. Male and female World Records in long distance running (dated 3rd December
493 2020). Data extracted from World Athletics records [10] and video observations.
494 Table 2. Shoes containing a rigid plate within the midsole currently available and technical
495 characteristics. Data have been obtained from different websites, articles and running shoe
496 blogs, with their cost corresponding to year 2020.