# IMPACT OF MASS GAIN, TAILWIND AND AGE IN THE PERFORMANCE OF USAIN BOLT FROM BEIJING 2008 TO RIO 2016

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ABSTRACT. Despite the impressiveness of the sprints performed by Usain Bolt, the question of why he has not been able to break his own 100 m sprint world record, set at Berlin (2009), naturally arises. In this paper, we address such a query by considering the conditions of Usain Bolt and the circumstances prevailing at the sprints that took place in Beijing 2008, Berlin 2009, London 2012, Moscow 2013, Beijing 2015 and Rio 2016[a]. Using the analytical mechanical model by Hernández-Gómez et al. [2013], we analyse all the events equating what we *a priory* thought were the principal factors: tailwind, weight-gain and age. Despite what one might expect about the role of the age in a high performance athlete as Usain Bolt, our results show that his performance has been essentially constant from Beijing 2009 to Rio 2016, being the mass gain and tailwind conditions the difference in the running times he has achieved after Berlin 2009. Actually, our analysis suggest that in equal mass and tailwind conditions, his world record would have actually been set at Beijing 2015.

*Keywords*: Usain Bolt, mechanical model, hydrodynamic drag, sport physics, 100 metre sprint, world record, Beijing 2008, Berlin 2009, Moscow 2013 and Beijing 2015 World Championships in Athletics, London 2012 and Rio 2016 Olympic Games.

## 1. INTRODUCTION

It is known that the effectiveness of a high-performance athlete with age first increases up to a maximum and from there on it starts to diminish. It seems that there is no way to determine at what age is such a maximum reached, because of the many factors (genetic, training technique, reaction time, possibility of disqualification, self-confidence, etc.) that intervene to establish it. The recent results in the 2016 Olympic Games (OG) and the 2017 Australian Open (AO) are good examples in which "old men" win younger ones: Michael Phelps wining 5 gold and 1 silver medals when he was 32 years old, and the final match between Rafael Nadal (31 years old) and Roger Federer (36 years old), won by the later. The unbeatable athletic trajectory of Usain Bolt (UB) in the World Championships in Athletics (WCA) and in the OG since he broke, in the 2009 Berlin WCA, his own 2008 Beijing OG 100 m sprint world record, deserves inquiring if he shall be able to do it again. The purpose of the analysis we make in this work is to investigate which factors could have influenced, in our opinion, the fact that he has not been able to implant again a new world record for such a distance. A question naturally arises: was 2009 the year when UB (23 years old) reached his maximum effectiveness? Incidentally, his 200 m sprint world record is from that same year.

Through years, several kinematic [Krzysztof and Mero, 2013], physiological [Charles and Bejan, 2009], and psychological [Varlet and Richardson, 2015] analysis have been published in which some of these factors are analysed. However, the way in which these factors are reflected in the performance of a runner are not easy to quantify. A more trustworthy way to get insight is through theoretical simulations [Vaughan, 1983*a*,*b*] of mechanical models in which several variables can be taken into account. Among the many models in the literature [Furusawa et al., 1927; Fenn, 1930; Keller, 1973; Shanebrook and Jaszczak, 1975; Holmlund and von Hertzen, 1997; Wagner, 1998; Alexandrov and Lucht, 1981; Pritchard, 1993; Helene and Yamashita, 2010; Barbosa et al., 2016; Janjić et al., 2017], in this paper we will concentrate in the successful mechanical model developed by Hernández-Gómez et al. [2013] for the 100 metre sprint, which we now apply to understand the performance of UB from Beijing 2008 to Rio 2016. To address the question of why he has not been able to break his own world record set at Berlin 2009, we evaluated with such a model the relevance of parameters such as the mass and age of the runner, as well as the sprint tailwind. We carefully show how to apply such a model to obtain substantial predictions on the subject, so any undergraduate student could get a physical insight into the physics of the 100 metre sprint, as well as into the application of mathematical models to real physical conditions. To do so, we structured this paper as follows: in

Section 2 we show the theoretical application of the referred model to other sprint events along with a practical example of its application to Rio 2016 OG; here we also analyze the impact of mass change of UB between Berlin 2009 and Rio 2016. In Section 3 we collect data of UB sprints from Beijing 2008 to Rio 2016 to get an insight of the main physical variables as the force and power exerted by him in such events. In Section 4 we fully exploit the predictive power of the model herein applied by simulating the events comprised in the time span before mentioned in three different hypothetical setups: if all have been run with the same tailwind conditions; if all have been run with the same UB's mass and; if all have been run with the same mass and tailwind conditions. The later allows us to isolate the age of the runner. Finally, in Section 5 we pose some interesting concluding remarks.

## 2. Theoretical model application

The mechanical model of the 100 metre sprint by Hernández-Gómez et al. [2013] followed two basic assumptions:

- That the 100 m sprinter is able to exert a constant force $F_0$ during the sprint; this assumption is based on the essentially constant speed UB develops in the 100 m and 200 m races in Berlin 2009, and has been successfully validated in [Hernández-Gómez et al., 2013], and
- That the air drag is proportional to both the speed and the square of the speed of the runner,

which yields to the following motion equation:

$$m\dot{v} = F_0 - \gamma v - \sigma v^2, \tag{1}$$

where $v$ is the speed of the sprinter, $m$ its mass, and $\gamma$ and $\sigma$ the air resistance and the hydrodynamical drag proportionality constants respectively. With the aid of extremely accurate measurements of UB's speed as a function of position in Berlin 2009, Hernández-Gómez et al. [2013] were able to fit the model parameters so as to obtain $F_0$, $\gamma$ and $\sigma$. Key features of UB, as his drag coefficient $C_d = 1.2$, were also obtained. With such a model, the possible running times with different tailwinds can be predicted by calculating the value of $\sigma'$ for each tailwind speed.

Some of the physical variables among different sprint events in which UB participated change and others do not:

(1) The air resistance term arises from air viscosity, which is independent of air pressure. The fitted $\gamma$ value turns out to be $\gamma = 59.7$ kg s$^{-1}$ [Hernández-Gómez et al., 2013].

(2) As the exerted constant force $F_0$ is particular of each runner and it depends on the specific conditions of the runner at the sprint moment, in this study we set $F_0$ as a parameter to be fitted.

(3) The estimation of the value of $\sigma$ for other sprint events can be done as follows: first, we take UB's drag coefficient $C_d = 1.2$ as well as his cross section area[a] $A = 0.8$ m$^2$ [Hernández-Gómez et al., 2013]. Then, air density at the sprint location is calculated considering its altitude above sea level as well as the temperature and humidity at the sprint moment; the latter values are taken from the official data sheets of the events. Then,

$$\sigma_s = \frac{1}{2}\rho C_d A\,.$$

(4) The above procedure calculates $\sigma_s$ in still air. To estimate its value in the wind conditions of the particular sprint (wind speed $v_w$), it is necessary to first estimate the terminal speed,

$$v_T = \frac{-\gamma + \sqrt{\gamma^2 + 4F_0\sigma_s}}{2\sigma_s}\,,$$

[a]Although his cross section area naturally changes with time, the method by which is estimated [Hernández-Gómez et al., 2013] is coarse enough not to distinguish slight changes in it in a relatively short time span ($\sim$ ten years).

so a first guess on the value of the parameter $F_0$ is required; for instance, the value it took in Berlin 2009. Then, the corrected hydrodynamical coefficient is given by [Hernández-Gómez et al., 2013]

$$\sigma = \sigma_s \left(1 + \frac{2v_w}{v_T}\right) .$$

(5) With the set value of the parameter $F_0$, $\gamma$ and the corrected value of $\sigma$, we compute the values of $A$, $B$ and $k$,

$$A = \frac{\gamma + \sqrt{\gamma^2 + 4F_0\sigma}}{2\sigma} ,$$
$$B = \frac{-\gamma + \sqrt{\gamma^2 + 4F_0\sigma}}{2\sigma} ,$$
$$k = \frac{\sqrt{\gamma^2 + 4F_0\sigma}}{m} ,$$

where $m$ can change from event to event. The explicit forms for the position $x(t)$, velocity $v(t)$ and acceleration $a(t)$ of the runner in such sprint are [Hernández-Gómez et al., 2013]:

(2)
$$x(t) = \frac{A}{k} \log\left(\frac{A + Be^{-kt}}{A+B}\right) + \frac{B}{k} \log\left(\frac{Ae^{kt} + B}{A+B}\right) ,$$
$$v(t) = \frac{AB\left(1 - e^{-kt}\right)}{A + Be^{-kt}} ,$$
$$a(t) = ABk(A+B)\frac{e^{-kt}}{\left(A + Be^{-kt}\right)^2} .$$

(6) In order to fit the value of the parameter $F_0$, equation (2) must be constrained as follows. If $t_s$ is the time of the sprint and $t_r$ is the runner's reaction time, it ought to follow that

$$x(t_s - t_r) = 100 \text{ m} .$$

This procedure is repeated recursively from steps (ii) to (vi), varying the values of $F_0$ until the above constriction is satisfied.

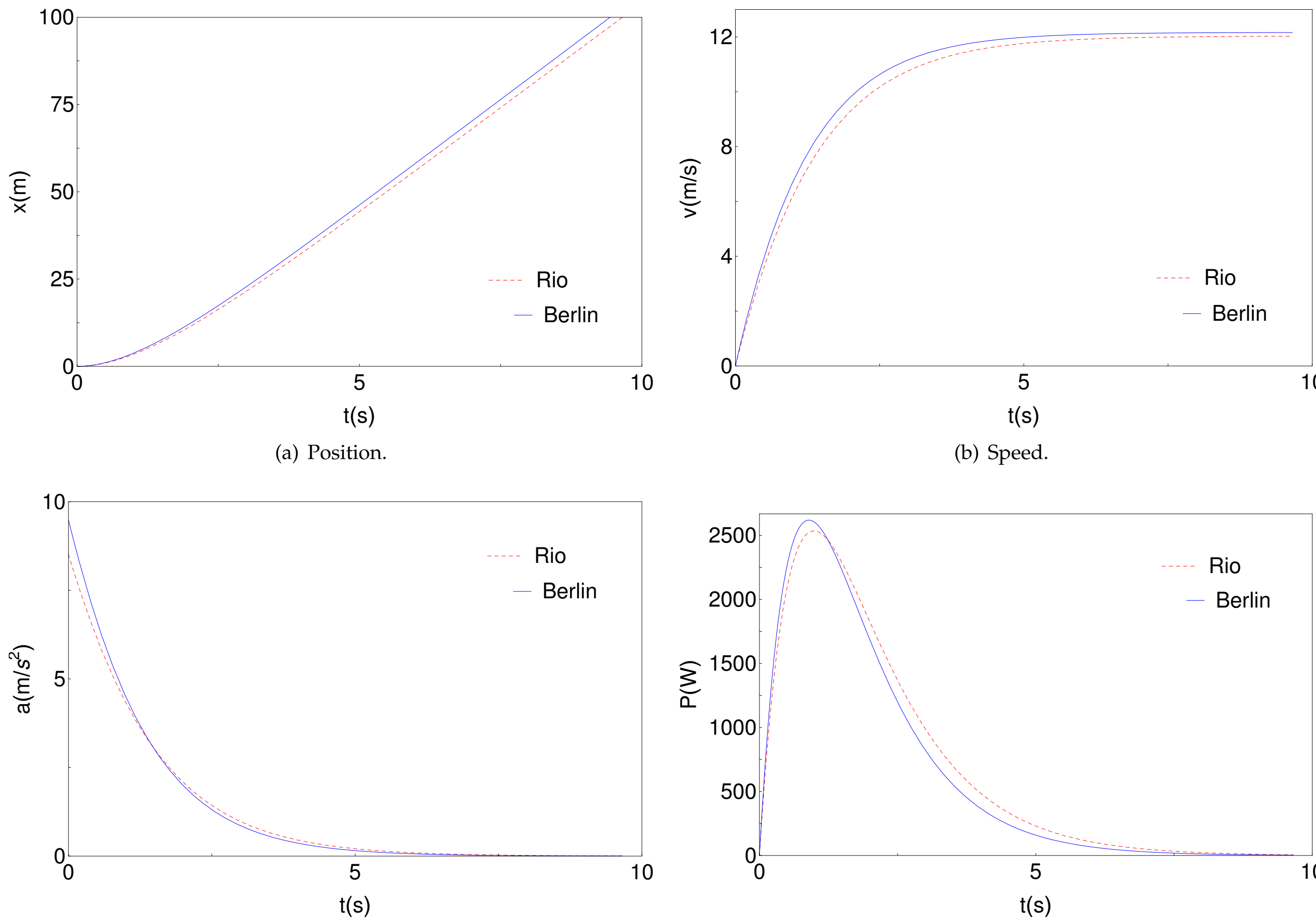
(7) When finishing this process, we end up with values of the physical parameters $F_0$, $\gamma$ and $\sigma$ which shall allow us to quantitatively observe the difference in the performance of UB in different competitions.

2.1. **Application example: Usain Bolt at Rio 2016 WO.** As mentioned in point (v), it is important to take the current UB's mass, which at Rio was $m = 94$ kg. This mass is 9.30% higher than the mass of 86 kg he had when he broke the world record at Berlin 2009 [Helene and Yamashita, 2010; Hernández-Gómez et al., 2013], so this increment ought to play an important role in the dynamics of the sprint at Rio. Taking into account $m = 94$ kg as well as Rio conditions (altitude of 11 masl, humidity of 53% and temperature of 23 C), $t_s = 9.81$ s and $t_r = 0.155$ s (see Table 3) [IAAF Rio 2016 World Olypmics, 2016], we obtain the physical parameters of the model for UB's 100 m sprint at Rio 2016 OG. These values are shown in Table 1, where we also present the corresponding values at Berlin 2009 [Hernández-Gómez et al., 2013] for comparison purposes.

TABLE 1. Values of the physical parameters $F_0$, $\gamma$ and $\sigma$ for both Berlin 2009 and Rio 2016.

| Constant | Value at Berlin 2009 | Value at Rio 2016 | Percent difference (%) |
|---|---|---|---|
| $F_0$ (N) | 815.8 | 800.7 | -1.85 |
| $\gamma$ (kg s$^{-1}$) | 59.7 | 59.7 | NA |
| $\sigma$ (kg m$^{-1}$) | 0.60 | 0.57 | -5.00 |

As it can be observed in Table 1, seven years after Berlin (2009), the exerted force by UB has reduced 1.85 % while $\sigma$ decreased 5.00 %. Although the changes are small, they are not negligible, as it is shown in Figure 1, where the overall performance of UB at Berlin 2009 and Rio 2016 can be appreciated. Figure 1(a) compares the position of UB as a function of time for both competitions. In both cases, after about the first two or three seconds, his speed persists essentially constant.




(a) Position.

(b) Speed.

(c) Acceleration.

(d) Power.

FIGURE 1. Position (a), speed (b), acceleration (c) and power (d) of Bolt in the 100 m sprint at both 12th IAAF WCA in Berlin (blue) and at 2016 Rio Olympics (dashed, red). Berlin 2009 graphs were plotted with the parameters obtained by data fitting in Hernández-Gómez et al. [2013].

From Figure 1(b) it is clear that the speed at Rio does not surpass the speed at Berlin at any moment. This is due, in part, to the fact that at Berlin 2009, he acquired a terminal speed of $v_T = 12.16$ m/s, while for the conditions of Rio 2016, it was of $v_T = 12.03$ m/s which is slightly lower. Also, there is a noticeable decrease in the initial acceleration of UB, shown in Figure 1(c): from $a(0) = 9.49$ m/s$^2$ (which was $0.97g$) at Berlin 2009 to $a(0) = 8.52$ m/s$^2$ (which is only $0.87g$) at Rio 2016. This 10.22 % reduction in the initial acceleration, notwithstanding that the force only decreases 1.85 %, is most likely due to his greater mass with respect to Berlin 2009. The 10.22 % reduction of the initial acceleration is consistent with the $\sim 9.30$ % in which UB's mass increased.

The instantaneous power he develops is given by [Hernández-Gómez et al., 2013]

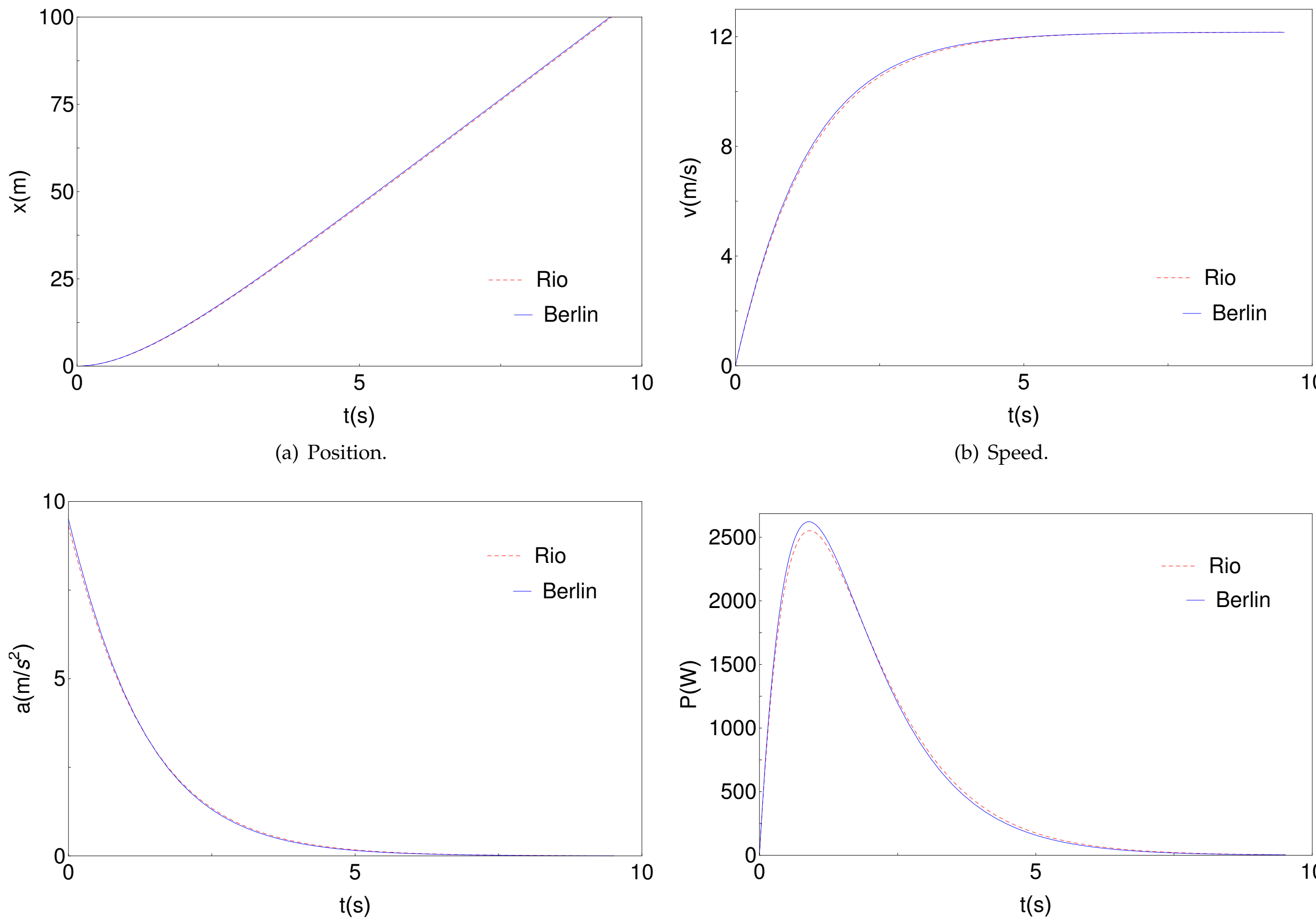
(3) $$P(t) = Fv = m\dot{v}v = m(AB)^2k(A+B)\frac{(1-e^{-kt})e^{-kt}}{(A+Be^{-kt})^3}.$$

In Figure 1(d) we plot the power of the sprint for both Berlin 2009 and Rio 2016, where distinguishable differences between both sprints are observed. While at Berlin 2009, the maximum power of $P_{max} = 2619.49$ W (3.51 HP) was reached promptly at a time of $t_{Pmax} = 0.89$ s, at Rio 2016 the maximum power reduces to $P_{max} = 2534.73$ W (3.40 HP) and it was reached at a time of $t_{Pmax} = 0.99$ s. Although the reduction is of just 3.24% with respect to Berlin 2009, the interplay of UB and the air drag is better observed when the full energy is calculated. While at Berlin 2009, the mechanical work exerted by UB is $W_{\mathrm{B}} = F_0 d = 81.58$ kJ, where $d = 100$ m, at Rio 2016 this value reduces to $W_{\mathrm{B}} = 80.07$ (-1.85%). Nevertheless, the effective work is [Hernández-Gómez et al., 2013]:

(4) $$W_{\mathrm{Eff}} = \int_0^{t_s-t_r} P(t)dt = \int_0^{t_s-t_r} \frac{1}{2}mdv^2 = \frac{1}{2}mv^2(t_s-t_r),$$

that is, the area under the curve of Figure 1(d), which at Berlin 2009 was $W_{\mathrm{Eff}} = 6.36$ kJ while at Rio 2016 was $W_{\mathrm{Eff}} = 6.80$ kJ. Although the effective work increased 6.92% with respect to Berlin 2009, this is simply explained by the fact that at Rio 2016 the achieved speed was lower than at Berlin 2009, so the drag terms which depend upon $v$ and $v^2$, dissipate less energy. Actually, while at Berlin 2009 the amount of energy used to achieve the motion was of 7.79% (of the total work exerted by UB in such an event), while at Rio 2016 was of 8.49% (*idem*).

2.1.1. *Impact of weight between Berlin 2009 and Rio 2016.* In order to gain physical insight of the impact of UB's weight gain in his sprinting performance, we predict his running time, if he have had a mass of $m = 86$ kg (mass of Berlin 2009 [Helene and Yamashita, 2010; Hernández-Gómez et al., 2013]) at Rio 2016. Assuming that despite the change in mass, he is able to exert essentially the same force as the one calculated in the previous section ($F_0 = 800.7$ N), taking the same value of $\sigma = 0.57$ because it does not depend on the runner mass, considering that his reaction time $t_r = 0.155$ s is essentially the same independently of his mass, and considering the same conditions of the sprint than in the previous section, we predict that UB would have run with a time of $t_s = 9.70$ s. Furthermore, if Rio 2016 have had the same tailwind conditions as in Berlin 2009 ($v_w = 0.9$), he's running time would have been of $t_s = 9.62$ s, slightly greater than Berlin 2009 world record (9.58 s) by just 0.04 s.




(a) Position.

(b) Speed.

(c) Acceleration.

(d) Power.

FIGURE 2. Position (a), speed (b), acceleration (c) and power (d) of Bolt in the 100 m sprint at both 12th IAAF WCA in Berlin (blue) as well as in the hypothetical 2016 Rio Olympics (dashed, red) with a mass of $m = 86$ kg. Berlin 2009 graphs were plotted with the parameters obtained by data fitting in Hernández-Gómez et al. [2013].

The overall performance of this hypothetical sprint is depicted in Figure 2, where again we show Rio 2016 against Berlin 2009 world record breaking performances. The great resemblance between our hypothetical sprint at Rio 2016 and the real one at Berlin 2009 is mainly due to the very similar circumstances in altitude, temperature and humidity at both races, despite the lower force exerted at Rio 2016. The latter fact allows us to emphasise the importance of the role of the mass in 100 m sprinters. To make a fair comparison, we calculated the sprint time of UB with his current mass of 94 kg, but with the same tailwind as in Berlin 2009 (0.9 m/s), which turns to be $t_s = 9.74$ s. These results are condensed in Table 2.

As it can be clearly observed from Table 2, the mass of the runner influences greatly the running times for the 100 m sprint, maybe even more than tailwind speeds. These results suggest that, at least for the 100 m sprint, runners should be categorised by their mass, just as in other sport disciplines as box, as to establish a fairer competition.

TABLE 2. Hypothetical running times at Rio 2016 with mass and tailwind conditions of both Rio 2016 and Berlin 2009. The real time is denoted in italics.

| $v_w$ (m/s) \ m (kg) | 86 | 94 |
|---|---|---|
| **0.2** | 9.70 | *9.81* |
| **0.9** | 9.62 | 9.74 |

## 3. USAIN BOLT'S PERFORMANCE THROUGH THE YEARS

To trace UB's performance through years from Beijing 2008 to Rio 2016 in a more precise way, a record of UB's mass in the intermediate years is required. We tried to contact UB's team to obtain an accurate record, but at the time of writing of this paper, we did not obtain any response[b]. Surprisingly, the increment in UB's mass was not linear between Beijing 2008 and Rio 2016 as it might be expected, but it was sudden between 2009 and 2012, as for London 2012 Olympics it was of $m = 93$ kg [BBC Sport, 2012]. The progression of UB's mass as well as other relevant data from each competition in which he obtained the first place in the 100 m sprint, are shown in Table 3.

TABLE 3. Key facts of Usain Bolt 100 m sprints at Berlin 2009, London 2012, Moscow 2013, Beijing 2015 and Rio 2016.

| Event | Bolt's mass m (kg) | Official time $t_s$ (s) | Reaction time $t_r$ (s) | Wind speed $v_w$ (m/s) | Temperature (C) | Humidity (%) | Altitude (m.a.s.l.) |
|---|---|---|---|---|---|---|---|
| **Beijing 2008**[c] | 86[d] | 9.69 | 0.165 | 0.0 | 21 | 71 | 43 |
| **Berlin 2009**[e] | 86[f] | 9.58 | 0.142 | +0.9 | 26 | 39 | 34 |
| **London 2012**[g] | 93[h] | 9.63 | 0.165 | +1.5 | 17 | 73 | 35 |
| **Moscow 2013**[a] | 93[b] | 9.77 | 0.163 | -0.3 | 21 | 62 | 156 |
| **Beijing 2015**[c] | 94[d] | 9.79 | 0.159 | -0.5 | 22 | 78 | 43 |
| **Rio 2016**[e] | 94 | 9.81 | 0.155 | +0.2 | 23 | 53 | 11 |

Some preliminary conclusions can be drawn from Table 3; for instance, from Berlin 2009 to London 2012, it seems that his reaction time might have been influenced by his 2011 disqualification in Korea, and that his second-best time was aided by a +1.5 m/s tailwind; nevertheless, his thirth-best time was obtained without tailwind. To acquire a better understanding of the evolution of UB's performance through years, the method depicted in Section 2 is now considered also for Beijing 2008, London 2012, Moscow 2013 and Beijing 2015.

In Table 4 we observe the overall evolution of UB's performance from Beijing 2008 to Rio 2016. The exerted force by UB (Table 4, Column 2) clearly decreases with his mass increment. Furthermore, at Berlin 2009, $F_0$ was 96.79%

[b]Although we carefully tried to trace the values of UB's mass in each event herein analysed from highly reputable sources, this was not possible. Thus, the values we report and use for the predictions of this section are the best ones available, or the most widely accepted/known ones.

[c]IAAF Beijing 2008: The XXIX Olympic Games [2008]; World Weather Online [2017]

[d]Helene and Yamashita [2010]

[e]IAAF Berlin 2009 World Championships in Athletics [2009]

[f]Helene and Yamashita [2010]; Hernández-Gómez et al. [2013]

[g]IAAF London 2012 World Olypmics [2012]

[h]BBC Sport [2012]

[a]IAAF Moscow 2013 World Championships in Athletics [2013]

[b]We were not able to retrieve the current mass of UB at Moscow 2013. Nevertheless, as at Glasgow 2014, UB's mass was reported as $m = 93$ kg [The Glasgow XX Commonwealth Games, 2013], we have supposed that his mass was constant from London 2012 up to 2014.

[c]IAAF Beijing 2015 World Championships in Athletics [2015]

[d]Herald Sun [2015]

[e]IAAF Rio 2016 World Olypmics [2016]

TABLE 4. Overall performance of Usain Bolt from Beijing 2008 to Rio 2016.

| Event | Exerted force $F_0$ (N) | Terminal speed $v_T$ (m/s) | Initial acceleration $a_0$ (m/s$^2$) | Maximum power $P_{max}$ (W) | Total work W (kJ) | Effective work $W_{eff}$ (kJ) |
|---|---|---|---|---|---|---|
| **Beijing 2008** | 804.7 | 12.04 | 9.36 | 2554.35 | 80.465 | 6.235 |
| **Berlin 2009** | 815.8 | 12.16 | 9.50 | 2619.50 | 81.580 | 6.360 |
| **London 2012** | 805.7 | 12.35 | 8.66 | 2594.96 | 80.570 | 7.078 |
| **Moscow 2013** | 808.9 | 12.06 | 8.70 | 2575.38 | 80.890 | 6.755 |
| **Beijing 2015** | 810.6 | 12.03 | 8.62 | 2579.88 | 81.057 | 6.798 |
| **Rio 2016** | 800.7 | 12.03 | 8.52 | 2534.73 | 80.070 | 6.795 |

of his weight at such an event; this percentage is of only 95.47%, 88.38%, 88.75%, 87.99% and 86.92% for Beijing 2008, London 2012, Moscow 2013, Beijing 2015 and Rio 2016 respectively. This latter fact reveals the direct impact of the mass in the ability of the sprinter to exert force. According to the model, in Table 4, Column 3, we feature the terminal speed that the runner could achieve. The particularly high value of achievable terminal speed at London 2012 was due to the higher tailwind at such a sprint. Nevertheless, due to the small exerted force (Table 4, Column 2) at this particular event, the maximum speed achieved by UB at London 2012 was of only $12.03$ m/s, much below the achievable terminal speed of $v_T = 12.35$ m/s at this sprint.

The influence of the mass in the performance of the 100 m sprinter is also revealed in Table 4, Column 4, in which we confirm the drastic decreasing in the initial acceleration of UB. Clearly, his initial acceleration reduced from $0.97g$ at Berlin 2009 to $0.95g$, $0.88g$, $0.89g$, $0.88g$ and $0.87g$ at Beijing 2008, London 2012, Moscow 2013, Beijing 2015 and Rio 2016 respectively.

In the last three columns of Table 4 we can observe the aspects of UB's performance related with energy. For instance, Table 4, Column 5 shows the maximum instantaneous power of UB, which is reached at $t_{P_{\max}} = 0.90$ s, $t_{P_{\max}} = 0.89$ s, $t_{P_{\max}} = 1.01$ s, $t_{P_{\max}} = 0.97$ s, $t_{P_{\max}} = 0.97$ s and $t_{P_{\max}} = 0.99$ s at Beijing 2008, Berlin 2009, London 2012, Moscow 2013, Beijing 2015 and Rio 2016 respectively. The particularly high time of achieving the maximum instantaneous power at London 2012 (1.01 s) is due to the particular high tailwind at such competition, which in turn reduces the relative speed of the sprinter and the medium, so the drag terms are smaller. This later effect can be clearer observed in Table 4, Columns 6 and 7 in which we show the total work done by UB, as well as the effective work (the energy effectively transformed to motion) respectively. It results that the effective work is only 7.75%, 7.80%, 8.78%, 8.35%, 8.39% and 8.49% of the total work for Beijing 2008, Berlin 2009, London 2012, Moscow 2013, Beijing 2015 and Rio 2016 respectively. In the particular case of London 2012, we see that despite the small differences in running times with Berlin 2009 (9.63 s and 9.58 s respectively), the total work exerted by UB to achieve 9.63 s at London was much minor than the one required at Berlin 2009. Likewise, the effective work was superior at London 2012, due to less dissipation by drag terms induced by the particular high tailwind.

## 4. HYPOTHETICAL USAIN BOLT'S PERFORMANCE THROUGH YEARS: EQUATING RUNNING CONDITIONS

As mentioned in the introduction, many factors can affect the effectiveness of a high-performance athlete. From the above analyses, it has been clearly revealed the impact of tailwind speed and mass of the runner in the running time of the 100 metre sprinter. Nevertheless, the question of the impact of the increment of age on the running time is still open. To tackle the age issue, we analyse the performance of UB from Beijing 2008 to Rio 2016 in three hypothetical cases: if all the events have occurred with the same tailwind; if all events have been run with the same mass and; if the events have had the same mass and tailwind conditions. The later hypothetical case would have removed the influence of tailwind and mass, so it ought to show the influence of age in UB's performance. These cases have been calculated with the methodology described in Section 2.

4.1. **2008-2016: Without tailwind.** The key physical facts of UB in the events from Beijing 2008 to Rio 2016 were recalculated with a standardised wind condition as if they have been run with no tailwind ($v_w^{(s)} = 0$). Clearly, the Beijing 2008 sprint is of particular importance as it was run without tailwind (see Table 3), so it does not change in this hypothetical case. Although several results regarding the physical parameters of UB in each event are illuminating, we only show the impact of the hypothesis in the running time, which is shown in Figure 3.

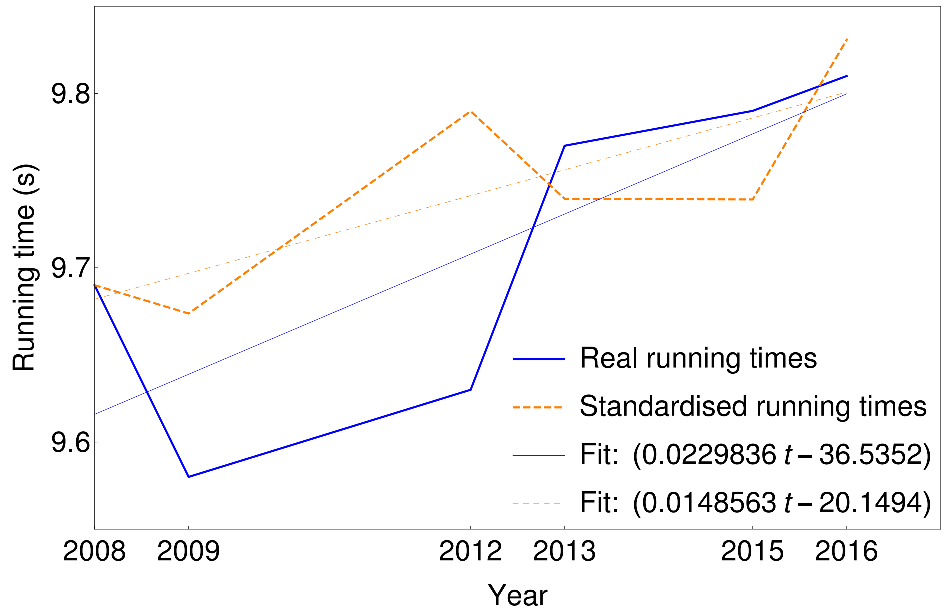



FIGURE 3. Real (blue, solid) *vs* wind speed standardised (orange, dashed) running times of Usain Bolt from Beijing 2008 to Rio 2016. For comparison purposes, the reported times include their respective reaction times.

We also condense the running time results in Table 5 for the no-tailwind case. The obtained results confirm the conclusion of Hernández-Gómez et al. [2013] regarding that a tailwind of $\pm 1.0$ m/s changes in approximately $\mp 0.1$ s the total sprint time.

TABLE 5. Hypothetical running times of Usain Bolt 100 m sprints at Beijing 2008, Berlin 2009, London 2012, Moscow 2013, Beijing 2015 and Rio 2016, calculated with the same tailwind conditions ($v_w^{(S)} = 0$ m/s).

| **Event** | **Original wind speed $\mathrm{v_w^{(O)}}$ (m/s)** | **Standardised wind speed $\mathrm{v_w^{(S)}}$ (m/s)** | **Original running time $\mathrm{t_O}$ (s)** | **Standardised running time $\mathrm{t_S}$ (s)** | **$\mathrm{t_O - t_S}$ (s)** |
|---|---|---|---|---|---|
| **Beijing 2008** | 0.00 | 0.00 | 9.69 | 9.69 | 0.00 |
| **Berlin 2009** | 0.90 | 0.00 | 9.58 | 9.67 | -0.09 |
| **London 2012** | 1.50 | 0.00 | 9.63 | 9.79 | 0.16 |
| **Moscow 2013** | -0.30 | 0.00 | 9.77 | 9.74 | +0.03 |
| **Beijing 2015** | -0.50 | 0.00 | 9.79 | 9.74 | +0.05 |
| **Rio 2016** | 0.20 | 0.00 | 9.81 | 9.83 | -0.02 |

4.2. **2008-2016: With the same mass.** The performance of UB in the events from Beijing 2008 to Rio 2016 was recalculated with a standardised mass of $m^{(S)} = 86$ kg, as if he would not have had any mass change from Berlin 2009 to Rio 2016 (including Beijing 2008). We assumed that the force he is able to exert do not change with his mass increments. Normally, a well-trained athlete can exert a greater force when he gains a small fraction ($\sim 5$ %) of his weight, so this assumption is only addressed for comparison purposes. Clearly, the Beijing 2008 sprint is of particular importance as it was run with the same mass of Berlin 2009, so it does not change in this hypothetical case.Although several results regarding the physical parameters of UB in each event are illuminating, we only show the impact of the hypothesis in the running time, which is shown in Figure 4.

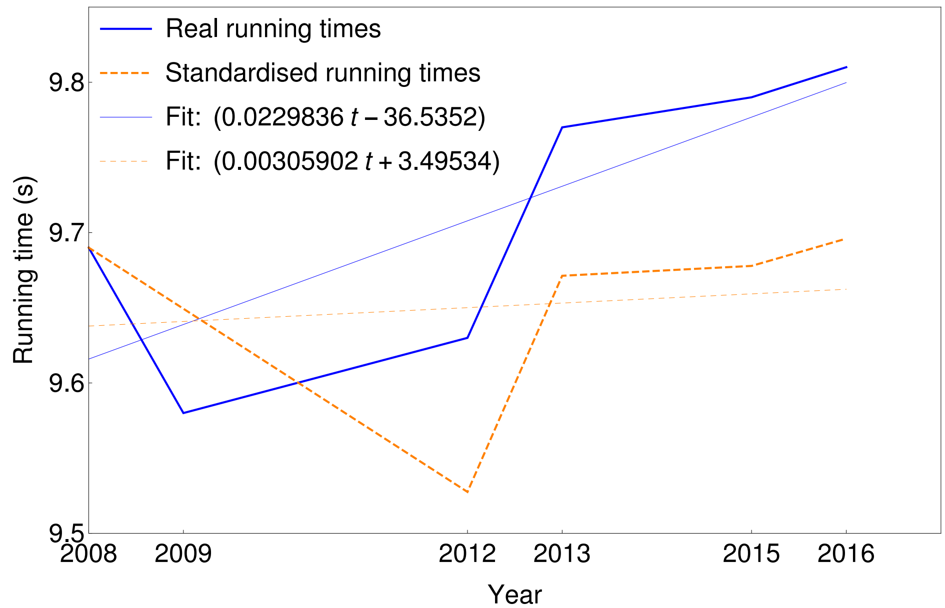



FIGURE 4. Real (blue, solid) *vs* mass standardised (orange, dashed) running times of Usain Bolt from Beijing 2008 to Rio 2016. For comparison purposes, the reported times include their respective reaction times.

The results of this hypothetical case has been summarised in Table 6. The average percent increase in UB mass was 8.02 %, whilst the average difference in $t_O - t_S$ is 0.11 s; this suggests that an eight percent of increase in mass outcomes in an increment of approximately 0.11 s in the running time. The running times in Table 6 consider the reaction time of UB in each event from 2008 to 2016, where we can observe that the world record under these conditions would have been established in London 2012 (9.53 s). It might be that if UB had not been disqualified at Korea 2011, he would have had a lower reaction time, perhaps closer to 0.142 (reaction time of Berlin 2009) at London 2012; in such a hypothetical case, if he also would not had gained weight, in the best case the 100 m world record would have been 9.51 s, favoured by the +1.5 m/s tailwind in such an event.

TABLE 6. Hypothetical running times of Usain Bolt 100 m sprints at Beijing 2008, Berlin 2009, London 2012, Moscow 2013, Beijing 2015 and Rio 2016, calculated as if they have been run with the same Bolt's mass as the one he had in Berlin 2009 ($m^{(S)} = 86$ kg).

| **Event** | **Original mass $m^{(O)}$ (kg)** | **Standardised mass $m^{(S)}$ (kg)** | **$m^{(S)}/m^{(O)}$ (1)** | **Original time $t_O$ (s)** | **Standardised time $t_S$ (s)** | **$t_S/t_O$ (1)** | **$t_O - t_S$ (s)** |
|---|---|---|---|---|---|---|---|
| **Beijing 2008** | 86 | 86 | 1.000 | 9.69 | 9.69 | 1.000 | 0.000 |
| **Berlin 2009** | 86 | 86 | 1.000 | 9.58 | 9.58 | 1.000 | 0.000 |
| **London 2012** | 93 | 86 | 0.925 | 9.63 | 9.53 | 0.989 | 0.102 |
| **Moscow 2013** | 93 | 86 | 0.925 | 9.77 | 9.67 | 0.990 | 0.099 |
| **Beijing 2015** | 94 | 86 | 0.915 | 9.79 | 9.68 | 0.989 | 0.112 |
| **Rio 2016** | 94 | 86 | 0.915 | 9.81 | 9.70 | 0.988 | 0.114 |

4.3. **2008-2016: Without tailwind and with the same mass.** Finally, the hypothetical performance of UB in the events comprised in the time span from 2008 to 2016 was calculated considering the same standardised wind conditions $v_w^{(S)} = 0$ m/s as well as with the same UB's standardised mass $m^{(S)} = 86$ kg. Clearly, the Beijing 2008 sprint is of particular importance as it was run in the same conditions as this standardised case, so it does not change in this hypothetical case. We again assumed that the exerted constant force has not changed from the one calculated in the real case. The results for the running times are shown in Figure 5.

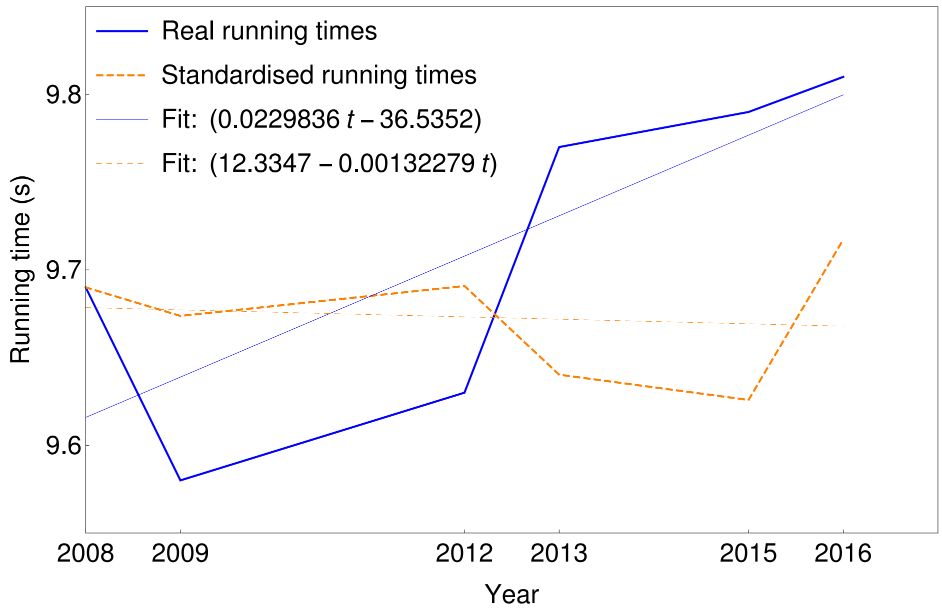



FIGURE 5. Real (blue, solid) *vs* both mass and wind speed standardised (orange, dashed) running times of Usain Bolt from Beijing 2008 to Rio 2016. For comparison purposes, the reported times include their respective reaction times.

From Table 7 we can observe that the mass and tailwind conditions affect linearly the running time result. Moreover, if UB would not have changed his mass from Berlin 2009, and if all sprint events would have been run under the same tailwind conditions ($v_w^{(S)} = 0$), the world record would have not been established in Berlin 2009 but in Beijing 2015, and would have been of 9.63 s. We must recall that these results contemplate the real reaction times of UB (see Table 3), which cannot be estimated under the hypothetical cases, as a psychological part takes an important role in reaction times besides the essential physiological and physical determining reasons. This way, in real terms, we could affirm that the best performance year of UB was 2015.

TABLE 7. Hypothetical running times of Usain Bolt 100 m sprints at Beijing 2008, Berlin 2009, London 2012, Moscow 2013, Beijing 2015 and Rio 2016, with the same tailwind conditions ($v_w^{(S)} = 0$ m/s) as well as if Bolt's mass did not change from that at Berlin 2009 ($m^{(S)} = 86$ kg)

| **Event** | **Original mass $m^{(O)}$ (kg)** | **Original wind speed $v_O$ (m/s)** | **Original time $t_O$ (s)** | **Standarised time $t_S$ (s)** | **$t_O - t_S$ (s)** |
|---|---|---|---|---|---|
| **Beijing 2008** | 86 | 0.00 | 9.69 | 9.69 | 0.00 |
| **Berlin 2009** | 86 | +0.90 | 9.58 | 9.67 | -0.09 |
| **London 2012** | 93 | +1.50 | 9.63 | 9.69 | -0.06 |
| **Moscow 2013** | 93 | -0.30 | 9.77 | 9.64 | +0.13 |
| **Beijing 2015** | 94 | -0.50 | 9.79 | 9.63 | +0.16 |
| **Rio 2016** | 94 | +0.20 | 9.81 | 9.72 | -0.09 |

With respect to the question of the impact of the age in the overall performance of UB in the time span herein considered, it is difficult to draw definite conclusions from the standardised results (see Figure 5). In one hand, the best and the worst running times, under the same mass and wind speed conditions, would had happen in the consecutive years 2015 and 2016. It is important to observe that the differences between the standardised running times are not as drastic as they are in real running times, which depicts an image of UB as a more stable athlete with respect to his performance as a 100 m sprinter. Nevertheless, the least square fit to the standardised data reveals that, from 2008 to 2016, his running time has remained essentially constant (see Figure 5). This result would suggest an answer to the question posed in the introduction of this paper, which would turn to be that in the particular case of UB, his performance has not seem to be affected by his age from his world record breaking 100 m sprint in Berlin 2009 up to Rio 2016 OG.

Although we know that we have very few data in order to interpret confidently the least square fits in Figures 3, 4 and 5, we just interpret those linear fits as main tendencies. Maybe with data of future events, the tendency would be clearer, allowing to perform a more conclusive fit.

## 5. Conclusions

In this paper we addressed the main query of why UB has not been able to break his own Berlin 2009 world record at the 100 metre sprint. Although we do not possess highly validated measurements of UB's mass for the different events herein studied, in light of their best available data for such masses, we conclude that his mass increment has been a determining factor for it, aided in some cases by the tailwind in particular events. With respect to the running times in standardised wind and mass conditions, naturally arises the question of whether the differences in standardised running times between different events may be considered as fluctuations from the almost constant running time shown by the data fit featured in Figure 5, or not; these fluctuations would be influenced by diverse mainly non-physical factors. Although we do not have enough results to state such a conclusion, this issue shall be illuminated by the performance of UB in the 100 m sprint at the 2017 IAAF World Championchips in Athletics, which shall be held at London from August 04th to 13th, 2017. If his running time in London 2017 is lower than at Rio 2016, we could then confirm that for his case, they are effectively fluctuations. But if his London 2017 running time results to be greater than his time at Rio 2016, that would mean that Beijing 2015 was his best year, and that from there, the age started to play an important role on UB's overall performance through years.

## 6. Future work

First of all, for future investigations it would be extremely useful for researchers to have access to accurate mass records of runners before each event. We think that a useful idea could be that the IAAF stablish a weight measure the of runners at the beginning and at the end of each sprint event, just as it is done for Formula One drivers. In such a case, this study could be repeated for other sprinters with a well-known mass record across the years. It would also be interesting for future studies to determine the influence of mass for high performance short sprinters in a controlled experimental environment. Maybe a suit that artificially adds different weights to the athlete equally distributed along its body in order to emulate a fatten process while minimising changes in his aerodynamics and/or drag coefficient would help to realise such a study. Those experimental investigations together with the conclusions of this paper are likely to have an influence on practice of the so called "queen" of track competitions in athletics.

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