



Research Article

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Lance Armstrong's Era of Performance - Part I: Are his Time Trial Performances Much Different from Other Winners?

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Abstract

In the aftermath of USADA's doping charges, Lance Armstrong eventually acknowledged the use of banned substances during his professional cycling career. Reckoning his confessions, we decided to evaluate Armstrong's sportive accomplishments by comparing his winning time trial achievements with achievements demonstrated by other riders in similar races over the years. In time trial racing, there are no collaborating riders on the course, making opportunities to profit from other riders' efforts through drafting impossible. Time trial performances thus solely depend on the strength and endurance of the individual rider. Accordingly, we argue that an examination of the 'historic' variation in these individual performances will increase chances to detect the influence of illicit doping aids on Armstrong's performances. In view of his doping use, we expected that his performances would be faster compared to performances of his counterparts in foregoing and succeeding years. We scrutinized archival records of the cycling sport and retrieved information concerning Armstrong's winning time trial performances ($N = 7$), realized in the Tour de France (1999–2005), as well as performances of other riders ($N = 55$) who, from 1934 to 2010, won races in the three European Grand Tours (Tour de France, Giro d'Italia, and Vuelta a España) and all faced time trial distances comparable to Armstrong's (50–61 km). We examined our research question by analysis of covariance (ANCOVA) with riders as the independent variable (Armstrong vs. the other riders) and mean km/h performances as the dependent variable in which we controlled for the influence of year of competition (i.e., the year in which riders won their time trial) and distances of the trials on riders' speed. ANCOVA initially revealed that Armstrong ($M_{\text{km/h}} = 49.37$) indeed raced faster relative to the other riders ($M_{\text{km/h}} = 44.67$, $p \leq 0.05$). However, this main effect disappeared ($p = 0.80$) after controlling for the influence of competition year on riders' performances, $b = 0.20$ km/h, $p \leq 0.001$. Distance did not have a significant influence, $b = -0.03$ km/h, $p = 0.84$. ANCOVA further indicated that all but one of Armstrong's performances fell within the bandwidth of the 68%–confidence interval. Reckoning the historic variation in riders' performances, Armstrong's achievements do not appear to be outstanding or atypical, implying that effects of the performance-enhancing doping aids he resorted to are limited. Alternatively, his performances can also be plausibly explained by

a gradual progress in speed over time, which is characteristic for professional cycling races such as the Tour de France.

Keywords

Archival data; Doping; Progress in road cycling performance; Time trial racing

Introduction

The synthetic glycoprotein hormone erythropoietin - best known as recombinant human erythropoietin (rHu-EPO) or epo - became widespread in endurance sports such as professional cycling in the beginning of the 1990s [1]. In 2000, the World Anti-Doping Agency (WADA) [2] implemented a test for epo, after which cyclists are said to have resorted to blood doping as an alternative for epo to boost their performances [2,3]. Since the 1990s, professional cycling suffered extensive doping scandals, all involving the illicit use of epo and / or blood doping, such as the 1998 Festina affair [4] and the 2006 Operação Puerto blood doping affair [5]. The last scandal concerns Lance Armstrong, the only rider ever to win seven consecutive Tours de France (1999–2005). Investigations by the United States Anti-Doping Agency (USADA) [6,7] led to allegations that between 1998 and 2005 the sportive achievements of Armstrong and eleven of his team mates at the U.S. Postal and Discovery Channel teams "were accomplished through a massive team doping scheme, more extensive than any previously revealed in professional sports history" [7]. The doping agents used by the accused cyclists predominantly involved epo, blood transfusions (doping with own blood, or with blood harvested from a compatible donor), and testosterone. Following charges put forward in USADA's 'Reasoned Decision' [7], the International Cycling Union (UCI) subsequently imposed sanctions on Armstrong: A lifetime ban from sports and a disqualification of his competitive results achieved since August 1, 1998, including his seven Tour victories. In January 2013, Armstrong acknowledged he doped. Note, however, that he never tested positive for any of the doping aids, alluded to above.

Ergogenic effect of epo and blood doping

Worldwide, the Armstrong affair evoked strong moral outrage and cleansing responses [8]: Doping regulations and tests should become more stringent; violations should be punished harsher; cyclists accused of doping use should be considered criminal offenders and treated likewise; team leaders, physicians, and trainers with a doping history should be banned from the sport; cycling should be barred from the Olympic Games; the sport should be forbidden; and television broadcasting of the Tour de France and popular one-day classic races should immediately be discontinued. These extreme punitive reactions appear to be fueled by shared beliefs about the strong performance-enhancing (or ergogenic) effects of epo and blood doping.

Research examining the relationship between epo / blood doping and aerobic performance builds on the cardiovascular / anaerobic model [9,10]. Table 1 depicts the proposed, causal chain of the model. The crucial variable in the model is VO_2 max, defined as an

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estimate of cardio-respiratory, circulatory and muscular fitness that measures the fastest rate at which oxygen can be utilized by the body during intense exercise. The model postulates that high levels of VO_2 max are a requirement for top-ranking achievements in endurance sports such as running, speed skating, cross-country skiing, and cycling [1]. Hemoglobin (Hb) is a protein in red blood cells (RBC or erythrocytes), which carries oxygen and, hence, it is essential in the chain of oxygen transport from the lungs to the muscles. The oxygen-transport capacity of blood can be increased by augmenting the blood's Hb concentration, or haematocrit (Ht). Ht constitutes the volume percentage of red blood cells in the blood. Thus, the theoretical grounds why endurance athletes such as cyclists are tempted to use Ht-augmenting doping aids (epo and blood doping) is because it is proposed that such an augmentation increases the blood's oxygen-carrying capacity, which, in turn, improves athletes' aerobic performance intensity (VO_2 max) and the associated maximal aerobic power output, expressed in watts (W). These improvements are proposed to result in increased speeds in races and, ultimately, even in victories.

In their recent review of findings of laboratory studies which examined the relationship between epo administration and aerobic performance, Lundby and Olsen [11] conclude that —if hematocrit (Ht) is artificially increased by epo administration from pre-test baseline values to around Ht = 50% post test - VO_2 max is estimated to improve by 8–12%. Over the years, these findings led to the generally shared opinion that the ergogenic effects of Ht-augmenting doping agents are 'dramatic' [12].

Research objective

Assuming that the findings of the studies described above are valid and given Armstrong's confessions of doping use and top-ranking cycling achievements, we argue that research should be able to detect the effects of illicit doping aids on his sportive feats. We propose that an analysis of the historic variation in riders' sportive achievements, demonstrated in the three European Grand Tours (Tour de France, Giro d'Italia, and Vuelta a España) over the years, will permit a critical evaluation of Armstrong's accomplishments. Hence, we decided to compare Armstrong's time trial achievements, which he realized in the Tour de France (1999–2005), with performances of riders who, from 1933 to 2011, all won time trials in the three European tours and faced time trial distances comparable to Armstrong's (50–61 km). Based on the arguments put forward above, we can expect that Armstrong's winning performances at these time trials will be faster compared to performances of his counterparts in foregoing and succeeding years. We have a specific reason for choosing time trial performances as the dependent variable to examine our research question. In a time trial, all riders face the same distance —20 km for example — and they individually compete for the fastest time. There are no collaborating riders on the course, making opportunities to profit from other riders' efforts through drafting (riding in other riders' slipstream) impossible. According to Lucia et al. [13] to maintain an average speed of ≥ 50 kilometers per hour (km/h) for longer periods of time, average riders must perform at high constant workloads during the entire trial; at or above ~90% of maximum oxygen uptake (VO_2 max) with estimated average power outputs of ~350W. Specialists are known to produce even higher average outputs of ~400–450W. Time trial performances thus solely depend on individual riders' strength and endurance. A critical appraisal of these individual performances will increase chances to detect the influence of ergogenic doping agents on riders'

velocity. Therefore, we argue that time trial performances are a sound criterion to critically examine Armstrong's disputed achievements.

Methods

Design, sample, and measurements

We scrutinized the archival records of the French "Association Mémoire du Cyclisme" [14] concerning the three Grand Tours and assessed winning time trial performances of Armstrong and the other riders from 1933 to 2011. The first time trial in professional road racing occurred in 1933 in the Giro, followed by the Tour in 1934 and by the Vuelta in 1941. We did not include team time trials, mountain time trials (racing uphill), and prologues in the study. In team time trials the total team participates in the race and the final performance results from coordinated group efforts. Hence, such performances are not individual performances. In 1967, organizers of the Tour de France scheduled the first 'official' prologue. It constitutes the first stage in the race and its maximal distance is approximately 8 km. Given the year 1967, the number of prologues would be too low to reach valid conclusions concerning our research question. The same argument holds for the number of mountain time trials which are rarely scheduled in the three races [13].

Descriptive statistics of the variables we assessed can be seen in Table 2. The number of time trials of riders who raced comparable distances is $N = 55$ and the years in which they demonstrated their performances range between 1934 and 2010. The total number of time trials for Armstrong is $N = 7$.

Table 3 presents the correlations between the variables included in the study. The relationships between year of competition and riders' performances are substantive, indicating that riders race faster over time ($r_{\text{km/h}} = 0.77$; $r_{\text{time}} = -0.71$). The correlation between year of competition and distance is not significant ($r = -0.18$). Table 3 further shows that the relationship between mean time and km/h performances is strong ($r = -0.95$). The correlation between distance and mean km/h performances is not significant ($r = -0.16$), whilst riders' mean time performances are significantly influenced by the distance variable ($r = 0.41$), i.e., increasing distances are associated with longer time performances.

Analyses

Given the design of the study and the variables we assessed, the differences in riders' mean km/h performances may be influenced by three sources of variation: riders, the year in which they competed, and the distances of the time trials. To estimate whether Armstrong indeed performed faster than the other riders, one should account for the influence of the latter two variables. Analysis of covariance (ANCOVA) permits an unbiased estimate of the rider main effect, since it allows one to statistically control for the influence of the other two variables (as covariates) on riders' performances. In our ANCOVA, riders served as the independent variable (dummy coded: other riders = 0; Armstrong = 1) and mean km/h performances as the dependent variable. To assess the influence of year of competition ($M = 1978$) and distance ($M = 54.86$ km) on riders' performances we mean centered these variables and included them as covariates in the analysis. ANCOVA follow-up further permits us to evaluate whether the feats of the American racer can be considered outliers, which are typically defined as $\pm 3SD$ from the sample mean [15]. However, to evaluate Armstrong's performances more critically, we decided to use the more stringent 68% ($\pm 1SD$) and 95% ($\pm 2SD$) confidence intervals to determine outliers.

Results

ANCOVA

Findings of ANCOVA are presented in Panels A, B and C of Table 4. Since we dummy-coded the independent variable (other riders = 0; Armstrong = 1), the intercepts in the various panels present other riders' mean km/h performances to which Armstrong's performances are compared. Panel A shows that the first step in the analysis produced a significant rider main effect, $b = +4.70 (\pm 2.33)$ km/h, $\eta_p^2 = 0.064$, which indicates that Armstrong ($M_{km/h} = 49.37$) indeed performed faster than the other riders ($M_{km/h} = 44.67$). However, the second step designates that, after including year of competition in the analysis, the rider main effect did not yield a significant effect anymore ($p = 0.80$).

As can be seen in Panel A, Armstrong ($M_{km/h} = 45.10$) even realized somewhat slower performances, $b = -0.43 (\pm 1.65)$ km/h, compared to the other riders ($M_{km/h} = 45.53$). This is due to the strong effect of competition year, $b = 0.20 (\pm 0.02)$ km/h, $\eta_p^2 = 0.57$, revealing that riders race 200 m faster per year. An additional Sobel test indicated that competition year significantly partialled out the rider main effect on performance, $z = 2.75$, $p \leq 0.01$, and the effect accounts for a substantial difference in riders' km/h performances over time, $b = 5.13 (\pm 1.86)$ km/h. The third step in Panel A designates that, after entering distance in ANCOVA, this variable did not significantly influence riders' performances, $b = -0.03 (\pm 0.17)$ km/h, $\eta_p^2 = 0.001$, $p = 0.84$. Thus, distance only mildly influences the effects presented in the second step of the analysis and competition year remains the

Table 1: Proposed Causal Model of the Epo Doping–Aerobic Performance Relationship.

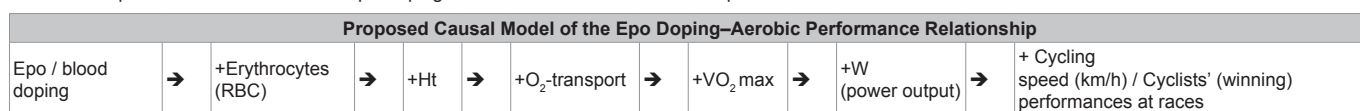


Table 2: Descriptive Statistics of Time Trial Performances and Riders Included in the Sample.

Descriptive Statistics of Time Trial Performances and Riders Included in the Sample						
Riders	N	Years (min- max)	M _{distance} (SD)	M _{time} (SD)	M _{km/h} (SD)	
Other riders	55	1934–2010	54.69 (3.09)	1:15:16 (0:14:11)	44.67 (6.06)	
Armstrong	7	1999–2005	56.21 (3.40)	1:08:22 (0:03:39)	49.37 (2.46)	
Total	62	1934–2010	54.86 (3.14)	1:14:29 (0:13:34)	45.20 (5.95)	

Note: Time = mean time performance in hours, minutes and seconds; km/h = mean kilometers per hour performance

Table 3: Intercorrelations between Variables Included in the Study (N = 62).

Intercorrelations between Variables Included in the Study (N = 62)				
Variables	1	2	3	4
1. Year of competition	-	-0.18	0.77**	-0.71**
2. Distance (km)		-	-0.16	0.41**
3. Mean kilometers per hour (km/h) performance			-	-0.95**
4. Mean time performance (in seconds)				-

** $p \leq 0.01$

Table 4: Results of ANCOVA: Riders' Mean Kilometers Per Hour Performances Controlled for Year of Competition and Distance of Time Trials (N = 62).

Results of ANCOVA: Riders' Mean Kilometers Per Hour Performances Controlled for Year of Competition and Distance of Time Trials (N = 62)							
	Step	Variables	F	b (SE _b)	95%-CI b	η_p^2	R ² _{adj}
A: ANCOVA	1	Intercept	-	44.67 (0.78)	43.10 – 46.23	-	-
		Rider	4.07*	+4.70 (2.33)	0.04 – 9.35	0.064	0.048
	2	Intercept	-	45.53 (0.53)	44.48 – 46.58	-	-
		Rider	0.07	-0.43 (1.65)	-3.72 – 2.86	0.001	-
		Year of competition	78.19***	0.20 (0.02)	0.15 – 0.24	0.570	0.584
	3	Intercept	-	45.51 (0.54)	44.44 – 46.59	-	-
		Rider	0.04	-0.35 (1.71)	-3.76 – 3.07	0.001	-
		Year of competition	71.03***	0.20 (0.02)	0.15 – 0.25	0.550	-
Distance		0.04	-0.03 (0.17)	-0.37 – 0.30	0.001	0.577	
B: ANCOVA (other riders)	1	Intercept	-	45.43 (0.50)	44.42 – 46.43		
	-	Year of competition	82.69***	0.20 (0.02)	0.15 – 0.24	0.588	
	-	Distance	0.11	-0.05 (0.16)	-0.38 – 0.27	0.002	0.578
C: ANCOVA (including interaction)	1	Intercept	-	45.48 (0.54)	44.41 – 46.56		
	-	Rider (A)	0.23	-0.85 (1.76)	-4.38 – -2.68	0.001	
	-	Year of competition	69.27***	0.20 (0.02)	0.15 – 0.24	0.549	
	-	Distance (B)	0.48	-0.10 (0.18)	-0.46 – 0.25	0.008	
	-	A x B	1.23	-0.55 (0.50)	-1.54 – 0.44	0.021	0.578

Notes: Regression weights and SEs are in kilometers per hour per year, or per kilometer increase in the distances of the time trials.

* $p \leq 0.05$; *** $p \leq 0.001$

strongest explanatory variable of riders' speed. Regarding Armstrong, the third step in Panel A again shows that he realized somewhat slower performances $b = -0.35 (\pm 1.71)$ km/h ($M_{\text{km/h}} = 45.16$), relative to the other riders ($M_{\text{km/h}} = 45.51$). Examination of the SE_b and 95%-CI in Panel A of Table 4 further reveal that, compared to the other riders, Armstrong's performances are characterized by a stronger variability. Most likely, this is due to the low number of his time trials ($N = 7$). To conclude, our findings do not support our research question and suggest that Armstrong's time trial performances are not faster relative to the other cyclists.

We performed some supplementary ANCOVAs to ascertain whether we are correct in our conclusion. One argument could be that the influence of competition year on riders' performances could be attributed to the specific years in which Armstrong demonstrated his sportive feats. We examined this question by conducting ANCOVA for the group of other riders separately (thus excluding Armstrong). Findings can be seen in Panel B of Table 4. They show that the influence of competition year is still significant, $b = 0.20 (\pm 0.02)$ km/h, $\eta_p^2 = 0.588$, and the obtained b -weight matches the b -weight obtained in Panel A which included Armstrong. Distance did not yield a significant influence, $b = -0.05 (\pm 0.16)$, $\eta_p^2 = 0.002$, $p = 0.74$. Accordingly, the overall linear influence of competition year on performance, which emerged from the first ANCOVA (Panel A), cannot be attributed to the specific years in which Armstrong realized his performances.

Although we found no distance effect for the total group of riders, it is conceivable that the effect of this variable on performance is different for Armstrong vs. the other cyclists. This comment implies a rider by distance interaction effect on mean km/h performances. We included the interaction term as an additional independent variable in ANCOVA. Findings can be seen in Panel C of Table 4. The analysis did not produce a significant interaction effect, $b = -0.55 (\pm 0.50)$ km/h, $\eta_p^2 = 0.021$, $p = 0.27$. All the other variables included in this model yielded results that are similar to the findings presented in Panels A and B. From these results we can conclude that, within the range of the 50–61 km distances of the time trials, Armstrong did not perform differently compared to the other riders.

Last, we conducted similar analyses using mean time performances as the dependent variable. In view of the strong relationship between mean km/h and time performances ($r = -0.95$), these analyses produced virtually identical results.

Outliers

Figures 1 and 2 graphically present the findings of ANCOVA described above. As to the influence of competition year, Figure 1 shows that all but one of Armstrong's performances fall within the limits of the 68%-CI, and all his performances did not exceed the 95%-CI. As regards distance, Figure 2 reveals the same pattern. It indicates that Armstrong's performances are evenly dispersed across the performances of the other riders. It also shows the variability in his performances, to which we referred to previously. Both figures further reveal that three riders realized relatively slow performances beyond the limits of the 95%-CI. They all occurred in the Vuelta in the 1940s: Rodriguez (1941, 1942) and Langarica (1946). These findings imply that, besides the feats of the three Spanish cyclists in the early years of the Vuelta, none of the performances achieved by the other riders can be considered outliers, including Armstrong's.

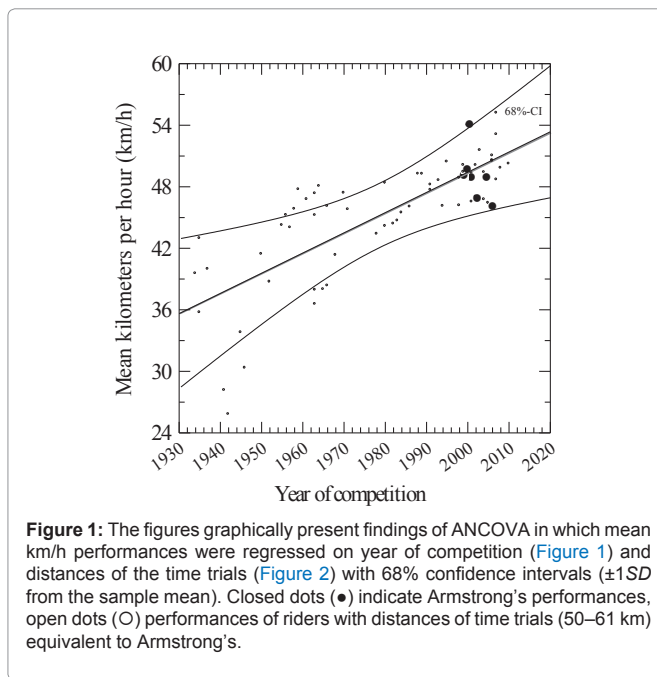


Figure 1: The figures graphically present findings of ANCOVA in which mean km/h performances were regressed on year of competition (Figure 1) and distances of the time trials (Figure 2) with 68% confidence intervals ($\pm 1SD$ from the sample mean). Closed dots (●) indicate Armstrong's performances, open dots (○) performances of riders with distances of time trials (50–61 km) equivalent to Armstrong's.

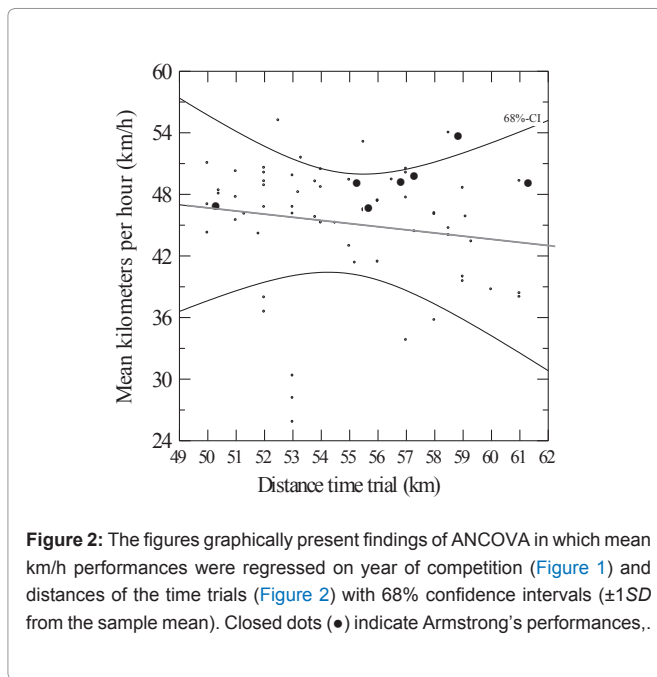


Figure 2: The figures graphically present findings of ANCOVA in which mean km/h performances were regressed on year of competition (Figure 1) and distances of the time trials (Figure 2) with 68% confidence intervals ($\pm 1SD$ from the sample mean). Closed dots (●) indicate Armstrong's performances.

Discussion

Based on USADA's charges [6,7] and Armstrong's subsequent assertions concerning his doping use, we designed this study to examine whether his time trial achievements, demonstrated in the Tour de France from 1999 to 2005, were faster compared to performances of other riders who, from 1934 to 2010, rode time trials in the three European Grand Tours that were equivalent to Armstrong's time trial distances (50–61 km). Our findings suggest that the achievements of the American cyclist are not faster or atypical. We arrive at this conclusion for the following reasons:

- Although he did realize faster performances in his time trials

relative to the other riders, the effect disappeared when we statistically controlled for the influence of competition year on riders' performances;

- Reckoning the variation in distances of the time trials, Armstrong's performances were evenly dispersed across the performances of the other riders;
- For both competition year and distance, findings showed that all but one of his performances did not exceed the bounds of the 68%–CI, and all his performances fell within the bandwidth of the 95%–CI.

These findings convincingly show that the achievements of the disputed American racer cannot be regarded outliers.

One factor may weaken our conclusion, which concerns the low number of Armstrong's time trials ($N = 7$). This reduces the statistical power of our analyses, which may have led us to make Type-II errors, i.e., we may have falsely concluded that there are no differences in speed between the riders, while such differences are, in fact, extant. However, various findings of our study make us confident that our conclusion is sound. One reason is that, when taking into consideration the very rigorous criterion of $\pm 1SD$ to determine outliers, only one of his seven performances did not meet this criterion. Another reason relates to the strong influence of competition year on riders' achievements. Our findings indicate that this variable explains about 58% of the variation in riders' mean km/h performances. Moreover, the same variable accounts for a difference of 5.13 km/h in riders' performances from 1934 to 2010. All riders' achievements are part and parcel of this continuing evolution in speed over time in professional road racing and the question can be posed: "Why would Armstrong's performances be an exception to this development?" To illustrate this, we compared Armstrong's performances with performances of the French rider Archambaud, former holder of the world-hour record. In 1935, Archambaud finished a 55 km-long time trial in 42.95 km/h (1:16:50). In 2004, Armstrong finished a trial of the same length in 49.39 km/h (1:06:49). Within a time span of ~ 70 years, Armstrong improved the achievement of the French rider with 6.44 km/h or ~ 10 minutes. However, findings of the regression analysis in [Figure 1](#) clearly show that Armstrong's 55 km-performance neatly falls within the bandwidth of performances that are predicted by competition year.

This finding, as well as other findings of our study, illustrate that Armstrong's performances are not outstanding. This implies that, although the use of illicit doping agents give cyclists an advantage, their ergogenic effects may be much smaller than generally assumed. In the following sections we will advance arguments that substantiate this conclusion. We will start with an expose concerning historic developments in professional road racing and extend it to doping use and its putative effects. Last, we will evaluate findings of studies that also examined archival records of the three European Grand Tours in professional cycling which yielded results that are inconsistent with the current findings.

Historic developments in cycling

Compared to Archambaud, many factors could have positively affected Armstrong's superior performance. Several of these factors concern typical race-related variables which are important in time trial racing, such as the conditions of the roads, the number of winding roads on the course, hilly terrains, and meteorological circumstances (wind, heat, rain). These factors may reasonably

account for the strong variability in Armstrong's performances which we observed. Other factors co-vary with competition year and they are summarized for example by El Helou et al. [16] and Lucia et al. [13]. They refer to technological innovations that do not only relate to bicycles and racing gear (weight and aerodynamics of the bikes, the use of derailleurs), but to growing insights from exercise physiology and associated developments in training practices as well [17,18]. Other variables concern riders' physical characteristics and capacities (age, body mass, VO_2 max / power output, biomechanical efficiency) [19] as well as their racing program which is much less demanding in the present era compared to the early days of the sport [20,21]. They further relate to external (social) factors such as staff support, financial incentives, nutrition, lodging and logistics during stage events, et cetera. All these race- and time-related factors put Armstrong's performances in a different perspective: Perhaps it is not that surprising that he raced ten minutes faster than Archambaud? We could even argue that the achievement of the French rider is really outstanding. In the 1930s, riders and their bikes were much heavier, they did not race with derailleurs, the roads were bad, and the conditions under which they practiced their sport were often brutal [13,16,20-22]. Nevertheless, in such circumstances, Archambaud managed to finish his 55 km-long time trial in a formidable 42.95 km/h.

Overestimated effects of doping?

Another variable is frequently heard to explain cyclists' achievements over the years: Doping use. This argument suggests the existence of a strong positive correlation between competition year and the use of increasingly more advanced and powerful doping means and methods, which ultimately would be responsible for riders' linear evolution in speed over time. For instance, in his inquisitive *Convicts of the Road*, French writer and journalist Londres [22] observed that riders used amphetamines in the 1923 Tour. Amphetamines were predominantly used in the 1940s, 1950s, and 1960s [17,21]. Hoberman [23] writes that anabolic-androgenic steroids became increasingly popular in sports (weight-lifting) in the late 1950s and in professional cycling in the 1970s [17,24]. However, former UCI president Verbruggen [25] contends that the ergogenic effects of both these doping agents on performances of endurance athletes such as cyclists are overestimated. What is more, studies [26,27] investigating the putative effects of doping in professional cycling suggest that the ergogenic effects of Ht-augmenting doping agents (epo and blood doping) might also be less distinct than generally assumed. Consistent with this latter conclusion, Heuberger et al. [28] in a critical review of the proposed physiological processes involved in the relationship between epo doping and aerobic performance rather boldly maintain that "there is no scientific basis to conclude rHuEPO has performance-enhancing properties in elite cyclists" and that the epo hypothesis lacks scientific evidence. If the observations of the latter studies are sound, they imply that the effects of Ht-augmenting doping aids on aerobic performance are overrated. In turn, this means that in real cycling races these effects might be overestimated too. Given the findings of our study, this conclusion might thus also hold true for Armstrong's time trial performances.

Related historic studies

Our findings do not agree with other studies that also examined archival records of the three European Grand Tours in professional cycling [16,29]. Perneger [29] investigated mean km/h performances of riders who reached the fifth place in the general classifications of

the three races in the period 1990–2009. He reported that between 1990 and 2004, riders' speed increased by 0.16 km/h per year and further observed a decrease in speed of 0.22 km/h per year since 2004. In 2000, WADA implemented a test for epo. In 2004, a test for homologous blood transfusions (blood harvested from a compatible donor) was implemented at the Summer Olympic Games in Athens [2]. Arguably, Perneger [29] attributed the incline in riders' mean speed to illicit doping practices and interpreted the decline since 2004 as evidence for the successes of WADA's anti-doping efforts. El Helou et al. [16] also investigated archival data of the cycling sport using a time-series model. They analyzed mean km/h performances of riders who reached the first ten places in the final rankings of eleven European races from 1892 to 2008, which included all famous one-day classic races as well as the three Grand Tours. They reported that, relative to the 1945–1992 periods, riders' mean km/h performances in the 1993–2008 period showed an improvement of 6.38%.

In disagreement with these results, however, our findings suggest a straightforward linear increase in performance from 1934 to 2010. The inconclusiveness of these findings may be due to differences in samples or to differences in dependent measures employed in the studies. We assessed individual riders' time trial performances, while the other studies examined riders' final achievements after three weeks of racing. As Perneger [29] already proposed, it is plausible to assume that these final performances may have come about through joint and coordinated efforts in the total group of riders participating in the race. These, often unknown (and, perhaps, inestimable) peloton efforts can be considered contaminating variables which may strongly impede a critical appraisal of individual riders' final performances after three weeks of competition in multi-stage cycling races. As we noted in the Introductory sections of this contribution, individual time trial performances are not affected by such group factors and may therefore constitute a more valid criterion to critically appraise developments in speed over time in professional road racing.

Conclusion

As is the case with all studies examining archival data of the cycling sport, the findings they generate can never be conclusive, because they lack essential control variables and base line conditions. Nobody knows how riders would have performed, had they refrained from taking banned substances. Of course, this criticism also holds true for the current study. Armstrong's confessions plausibly suggest that his performances were boosted by illicit doping aids. Yet, our observations indicate that his accomplishments are not atypical or outstanding. This implies that the physiological, performance-enhancing advantages of these doping aids appear to be limited. Conversely, one cannot easily rebut the argument that the achievements of the American racer are also strongly influenced by the time- and race-related factors alluded to above. Admittedly, our study does not resolve this issue. However, recent studies examining historic developments in speed in the three European Grand Tours from 1903 to 2011 [30,31] show that these factors constitute important explanatory variables, which account for a very substantial $\pm 98\%$ of the variation in riders' performances. These historic studies emphasize that it is worthwhile to intricately assess the influence of these factors on riders' sportive achievements. Perhaps, findings of these future studies could also temper the extremity in the punitive, moral reactions evoked by the Armstrong affair.

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