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Trend Forecasting in Swimming World Records and in the Age of World Record Holders

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Abstract: This study aimed to forecast trends in swimming world records (WRs) and in the age of record holders. A total of 566 individual freestyle WRs (290 for males and 276 for females) were retrieved from open access websites. The frequency of observations in WRs in each decade and event was computed for males and females. The swimmers' chronological age was converted into decimal age at the time of breaking the world record. ARIMA forecasting models and exponential smoothing techniques were used to examine historical trends and predict future observations. The WRs improved over time, and there was a nuanced pattern in the age of world record holders. While certain events (50 m and 100 m) showed swimmers achieving records at older ages, others (e.g., 200 m, 400 m, 800 m, and 1500 m) displayed variations. Forecasting shows a continuing improvement in WRs in the upcoming years, with the age of male world record holders stabilizing in shorter events and decreasing in longer distance ones, while for females, general stabilization should be expected for the majority of competitive events.

Keywords: swimmers; performance; decades; prediction; freestyle

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1. Introduction

Success in competitive swimming requires a clearly defined pathway of progression to deliver the best performances in adulthood. In the past, several backcourt strategies have been implemented to help swimmers have a longer and more sustainable career. The implementation of Long-Term Athletic Development models [1,2] or performance monitoring over swimmers' careers [3–5] contributed to understanding how swimmers behave over the years and how they may improve in the long-term. Moreover, the determination of normative data and percentile curves [6] and the comparison of age-related performance progression against top athletes [7] have also been used for tracking swimmers headed toward future success.

At some point in a swimmer's career, there will be stabilization in their performance near the peak. The age range between 15 and 16 years has been considered a determinant for achieving the best individual performance in long-distance events [8]. Males' peak individual performance seems to occur between 18 and 19 years for short-distance specialists and between 17 and 18 years for long-distance specialists [9]. The analysis of overall trends and the individual paths of performance over a decade showed deceleration around the age of 16 years [4], with the peak performance being reached around 18–19 years for young adults [10].

World-class performances are also highly dependent on swimmers' sex. Allen et al. [7] concluded that top male swimmers achieved peak performance ~2 years later than their female counterparts. This difference in age of peak performance between sexes appears to be explained almost entirely by the ~2-year earlier onset of puberty in females compared with males [11]. However, during recent decades, the improved performance of elite female athletes has narrowed the gap by 8 to 12% compared to male athletes [12]. Despite that, some genetic traits related to athletic development and peak performance will always persist [13], not allowing for the complete disappearance of this gender gap.

As swimmers grow older, they may become unwilling or physiologically unable to sustain the training loads required to achieve top performances in their events. Although these swimmers may endure the training loads, the continuous training stress may increase their susceptibility to injury [14]. This scenario could result in a premature peak in performance, leading to a career break or a drop-out. As a consequence, most of these decisions are taken to pursue other challenges like parenting, pursuing an academic/professional career, or even just recovering from the emotional or physical exhaustion induced by training [15]. Still, if they return to practice a few years later, they can compete at an elite level (e.g., Dara Torres, Rūta Meilutytė, or Cody Simpson).

Recent top-level performances in shorter distances (including some in World and Olympic events) were achieved by swimmers who were over 30 years old (e.g., Roland Schoeman, Jason Lezak, Marleen Veldhuis, Nicholas Santos, Sarah Sjöström). It seems that some of today's top-ranked swimmers are winning at a more advanced age than their previous counterparts. Knetchle et al. [16] found that the age of peak performance of World and Olympic champions competing between 1992 and 2013 was ~2–3 years older compared with Olympic gold medal winners (aged ~21 and ~23 years) from 1896 to 1980. Rust et al. [17] also found that the age of peak swimming speed for elite female swimmers increased in the 50 m freestyle from 1994 to 2012.

World records in long-course freestyle swimming have constantly improved over the decades, influenced by changes in training practices and/or technology. However, it remains unclear if there is a preference in the age of world record holders across different types of freestyle events (short-distance vs. long-distance). Studying world record dynamics based on historical data can provide insights into world record trends and whether they differ by sex and event type. As athletes continually strive for excellence, it is intriguing to examine whether there is a shift in the age at which swimmers achieve those world records. To the best of the authors' knowledge, there is a lack of research on world records in swimming, as no research has been conducted in this context. So, there is a chance here to conduct a deeper analysis of world record trends and predict what can happen in the years to come.

This study aimed to achieve the following: (i) perform a comprehensive analysis of historical data on swimming world records; (ii) identify patterns and trends in world records and in the age of record-breaking athletes; and (iii) predict the next two world records and the age of the world record holders. The following has been hypothesized: (i) there is a trend of improvement in world records over time in long-course events; (ii) the age of world record holders differs between short-distance and long-distance freestyle events; (iii) future world records might be accurately predicted based on historical data, with discrepancies in trends based on sex and event type.

2. Materials and Methods

2.1. Design

An observational retrospective and prospective design was selected for the present study. A comprehensive dataset of swimmers' demographics and world records (WRs) in freestyle swimming events was compiled by two independent researchers consulting open access websites (e.g., swimrankings.net; omegatiming.com; worldaquatics.com). The time frame of this study covered 10 decades to capture long-term trends. As such, the WRs in 50 m, 100 m, 200 m, 400 m, 800 m, and 1500 m freestyle events (long-course) from 1920 up to 2019 were considered. The event, swimmer's name, chronological age, and date of the record were extracted for each swimming event and grouped by decade (e.g., 1920–1929). The chronological age of each swimmer was converted into decimal age at the time of breaking the world record. A total of 566 individual WRs (290 for males and 276 for females) were included for further analysis. All records have been converted from min to s if applicable to the event. The Institutional Ethics Committee stated that ethics approval was not required for this type of study design.

2.2. Statistical Analysis

The frequency of observations in WRs in each decade and event was computed. The Kolmogorov–Smirnov test was used to analyze the normality assumption. The mean plus one standard deviation was used for descriptive statistics and divided according to sex. Since the aim was to detect overall temporal trends across decades, rather than specific interdecadal comparisons, a one-way ANOVA was used to assess differences in WRs and in the age of world record holders between decades. The Levene test was used to evaluate the homogeneity assumption. The effect size was collected through Eta Squared (η^2) and interpreted according to Ferguson as follows [18]: no effect if $\eta^2 \leq 0.04$, a minimal effect if $0.04 > \eta^2 \leq 0.25$, a moderate effect if $0.25 > \eta^2 \leq 0.64$, and a strong effect if $\eta^2 > 0.64$).

Autoregressive Integrated Moving Average (ARIMA) models were used to examine historical trends and predict future observations among WRs and the age of world record holders. For this purpose, a univariate time series was used with a sequence of measurements of the same variable collected over time. For each model, the forecast started after the last non-missing value in the range of the requested estimation period and ended at the last period for which non-missing values of all of the predictors were available or at the end date of the requested forecast period, whichever was earlier. This approach allowed each event to be described in terms of time and/or age as either increasing, decreasing, or stabilizing. Just two observations were considered for the description of the forecast trends within the next decade.

All statistical analyses were performed using SPSS software (v.27, IBM, SPSS Inc., Chicago, IL, USA), with statistical significance set at $p \leq 0.05$.

3. Results

Table 1 shows the frequency of WRs in freestyle events over the decades according to sex. While there was a trend for a higher frequency of WRs in both groups between the 1960s and the beginning of the 21st century, it has slowed down in the last decade.

Table 1. The frequency of WRs in freestyle events (long-course pool) over the decades according to sex.

	Decades									
	1920–1929	**1930–1939**	**1940–1949**	**1950–1959**	**1960–1969**	**1970–1979**	**1980–1989**	**1990–1999**	**2000–2009**	**2010–2019**
Males										
50 m	--	--	--	--	--	3	15	2	7	--
100 m	3	3	3	4	7	9	5	1	8	--
200 m	4	1	2	9	17	9	8	3	8	--
400 m	5	3	4	10	13	14	7	4	5	--
800 m	6	7	5	5	6	13	3	3	4	--
1500 m	6	--	2	4	9	11	3	4	1	2
Females										
50 m	--	--	--	--	--	2	13	2	8	1
100 m	7	6	10	5	13	3	2	11	2	--
200 m	3	6	--	5	7	14	2	1	8	--
400 m	7	9	2	2	13	12	2	--	6	3
800 m	--	4	1	6	9	19	4	--	1	5
1500 m	4	3	2	1	10	11	2	--	1	6

Table 2 shows the differences between decades in mean WRs according to sex. There was a natural trend of improvement in WRs over the decades, with a strong effect in all of the events analyzed.

Table 2. Differences between decades in mean WR times (in s) according to sex.

	Decades										One-Way ANOVA		
	1920–1929	**1930–1939**	**1940–1949**	**1950–1959**	**1960–1969**	**1970–1979**	**1980–1989**	**1990–1999**	**2000–2009**	**2010–2019**	**F**	***p***	**η^2**
Males													
50 m	--	--	--	--	--	23.77 ± 0.08	22.56 ± 0.43	21.90 ± 0.12	21.32 ± 0.36	--	34.44	<0.01	0.82
100 m	58.80 ± 1.51	56.60 ± 0.20	55.70 ± 0.26	55.00 ± 0.37	53.03 ± 0.74	50.81 ± 0.78	48.94 ± 1.37	48.21 *	47.44 ± 0.43	--	147.71	<0.01	0.97
200 m	134.65 ± 4.90	127.20 *	125.80 ± 0.57	123.12 ± 1.51	117.85 ± 2.35	111.65 ± 1.53	107.90 ± 0.85	106.34 ± 0.34	104.35 ± 1.36	--	132.75	<0.01	0.95
400 m	300.08 ± 8.86	284.03 ± 4.63	275.15 ± 2.38	265.24 ± 4.88	250.42 ± 3.15	236.12 ± 4.52	228.82 ± 1.63	224.28 ± 1.96	220.45 ± 0.54	--	235.80	<0.01	0.97
800 m	642.03 ± 15.17	610.66 ± 9.10	583.54 ± 5.77	555.64 ± 11.06	521.80 ± 8.67	492.53 ± 8.99	471.90 ± 1.13	466.82 ± 0.94	457.88 ± 4.05	--	287.54	<0.01	0.98
1500 m	1233.32 ± 56.56	--	1107.35 ± 11.81	1071.75 ± 16.26	1001.54 ± 24.60	930.24 ± 18.96	896.46 ± 1.76	885.98 ± 4.08	874.56 *	872.58 ± 2.21	90.23	<0.01	0.96
Females													
50 m	--	--	--	--	--	26.87 ± 0.18	25.67 ± 0.44	24.65 ± 0.20	24.16 ± 0.28	23.67 *	35.76	<0.01	0.87
100 m	71.74 ± 2.01	65.90 ± 1.27	62.67 ± 1.16	59.70 ± 0.51	57.14 ± 1.17	54.83 ± 0.13	54.25 ± 0.83	53.10 ± 0.62	51.89 ± 0.25	--	204.61	<0.01	0.97
200 m	164.47 ± 3.56	147.07 ± 4.41	--	138.18 ± 2.24	129.24 ± 1.63	121.84 ± 2.92	117.65 ± 0.14	116.78 *	115.00 ± 1.28	--	170.99	<0.01	0.97
400 m	354.25 ± 18.72	315.71 ± 8.55	302.75 ± 3.75	289.00 ± 2.55	276.64 ± 6.65	255.01 ± 6.13	244.65 ± 1.13	--	241.15 ± 1.37	237.90 ± 1.27	126.42	<0.01	0.96
800 m	--	702.23 ± 27.89	652.50 *	621.73 ± 12.36	573.03 ± 16.29	525.90 ± 12.09	498.83 ± 2.78	--	494.10 *	488.57 ± 3.35	133.26	<0.01	0.96
1500 m	1454.75 ± 35.87	1353.20 ± 45.85	1263.55 ± 9.26	1246.50 *	1001.28 ± 42.24	997.49 ± 20.14	956.42 ± 6.10	--	942.54 *	928.80 ± 5.85	153.53	<0.01	0.98

* Single WR.

Table 3 shows the differences between decades in the mean age of world record holders according to sex. Preliminary data analysis reveals a nuanced pattern in the age of world record holders. While certain events (e.g., 50 m and 100 m) show a consistent trend of swimmers achieving records at older ages over the decades, other events (e.g., 200 m, 400 m, 800 m, and 1500 m) display variations.

Table 3. The differences between decades in the mean age (decimal age) of WR holders according to sex.

	Decades										One-Way ANOVA		
	1920–1929	**1930–1939**	**1940–1949**	**1950–1959**	**1960–1969**	**1970–1979**	**1980–1989**	**1990–1999**	**2000–2009**	**2010–2019**	**F**	***p***	**η^2**
Males													
50 m	--	--	--	--	--	23.44 ± 1.88	21.84 ± 2.42	25.46 ± 0.00	24.58 ± 2.69	--	2.92	0.05	0.28
100 m	22.61 ± 6.45	21.20 ± 0.97	20.18 ± 1.41	22.26 ± 2.64	21.06 ± 1.80	21.05 ± 1.62	21.07 ± 1.37	22.59 *	23.64 ± 1.17	--	1.30	0.28	--
200 m	21.23 ± 2.24	20.52 *	18.72 ± 1.44	19.26 ± 2.55	20.08 ± 2.21	19.58 ± 1.99	20.48 ± 1.38	17.53 ± 1.16	20.85 ± 2.44	--	1.16	0.34	--
400 m	20.97 ± 2.67	19.98 ± 1.76	19.36 ± 1.89	18.76 ± 2.03	19.24 ± 2.12	18.01 ± 0.94	20.78 ± 1.34	19.02 ± 1.76	19.41 ± 2.17	--	2.15	0.05	0.24
800 m	20.18 ± 3.66	19.70 ± 2.35	20.14 ± 1.65	17.57 ± 2.37	21.11 ± 1.94	16.91 ± 1.07	23.58 ± 2.24	19.19 ± 1.61	21.25 ± 3.23	--	4.75	<0.01	0.47
1500 m	22.53 ± 3.17	--	20.91 ± 0.01	18.94 ± 2.63	20.45 ± 2.33	17.57 ± 2.69	21.49 ± 1.31	19.90 ± 1.27	21.22 *	20.17 ± 0.72	2.52	0.03	0.38
Females													
50 m	--	--	--	--	--	17.91 ± 1.64	17.02 ± 1.38	23.65 ± 4.38	25.94 ± 3.27	23.95 *	19.27	<0.01	0.79
100 m	18.48 ± 1.01	16.78 ± 1.02	19.12 ± 1.20	22.48 ± 4.65	16.98 ± 3.38	20.87 ± 0.29	19.25 ± 0.34	23.93 ± 2.71	24.11 ± 0.25	--	8.54	<0.01	0.58
200 m	18.52 ± 3.04	16.48 ± 1.14	--	19.07 ± 1.28	17.41 ± 2.55	16.28 ± 1.39	17.23 ± 1.50	16.42 *	20.75 ± 1.63	--	5.87	<0.01	0.52
400 m	18.15 ± 1.45	17.22 ± 0.86	19.75 ± 0.01	17.98 ± 0.11	16.67 ± 1.05	16.54 ± 1.14	16.69 ± 0.54	--	20.57 ± 1.13	18.07 ± 1.14	9.86	<0.01	0.63
800 m	--	21.15 ± 3.82	20.67 *	15.72 ± 2.56	15.79 ± 1.44	16.26 ± 1.49	17.11 ± 1.04	--	19.49 *	18.06 ± 1.22	5.22	<0.01	0.47
1500 m	18.52 ± 1.86	18.03 ± 0.45	20.18 ± 0.72	16.27 *	15.47 ± 1.06	15.10 ± 1.20	16. 25 ± 0.45	--	18.97 *	18.16 ± 1.65	8.14	<0.01	0.68

* Single WR holder.

Figures 1 and 2 show the forecast models for the next two WRs in male and female freestyle events, respectively. The future observations show a natural improvement in WRs for both sexes in the upcoming decades.

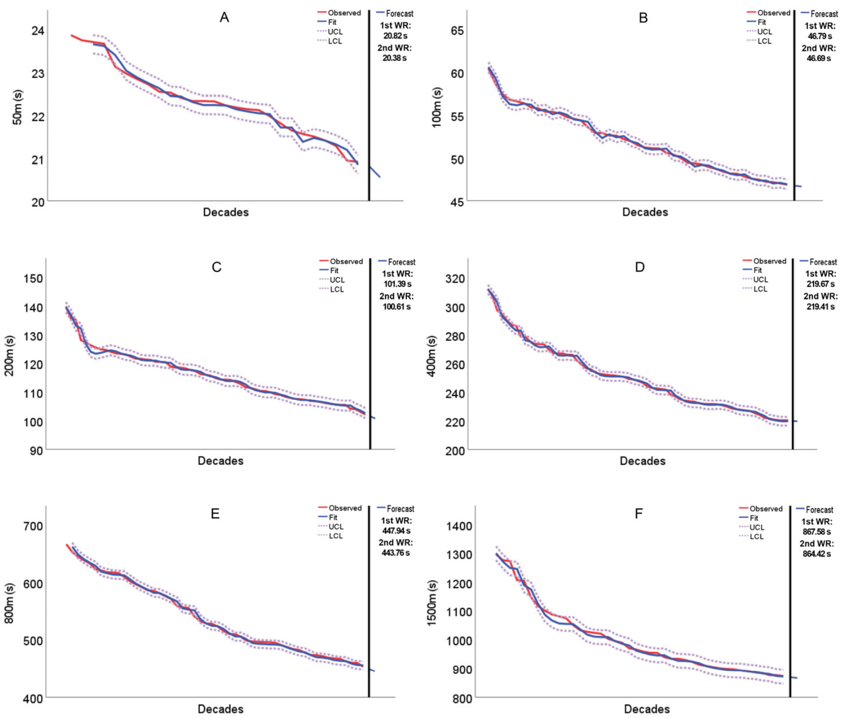

Figure 1. Forecast models for predicting male WRs in all freestyle events (panel (**A**), 50 m; panel (**B**), 100 m; panel (**C**), 200 m; panel (**D**), 400 m; panel (**E**), 800 m; panel (**F**), 1500 m). Fit: line of best fit; UCL: upper confidence limit; LCL: lower confidence limit; WR: predicted time for world record.

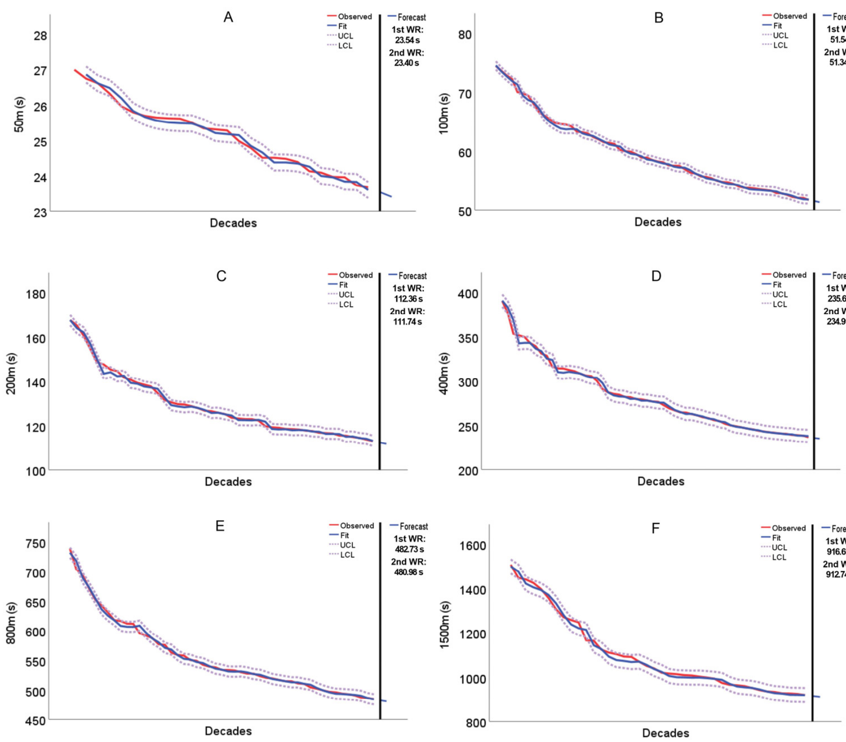

Figure 2. Forecast models for predicting female WRs in all freestyle events (panel (**A**), 50 m; panel (**B**), 100 m; panel (**C**), 200 m; panel (**D**), 400 m; panel (**E**), 800 m; panel (**F**), 1500 m). Fit: line of best fit; UCL: upper confidence limit; LCL: lower confidence limit; WR: predicted time for world record.

Figures 3 and 4 show the forecast models for the next two ages of male and female world record holders, respectively. The future observations show that the age of male world record holders seems to stabilize in shorter events and decrease in longer distance ones, while for females, general stabilization should be expected for the majority of the events.

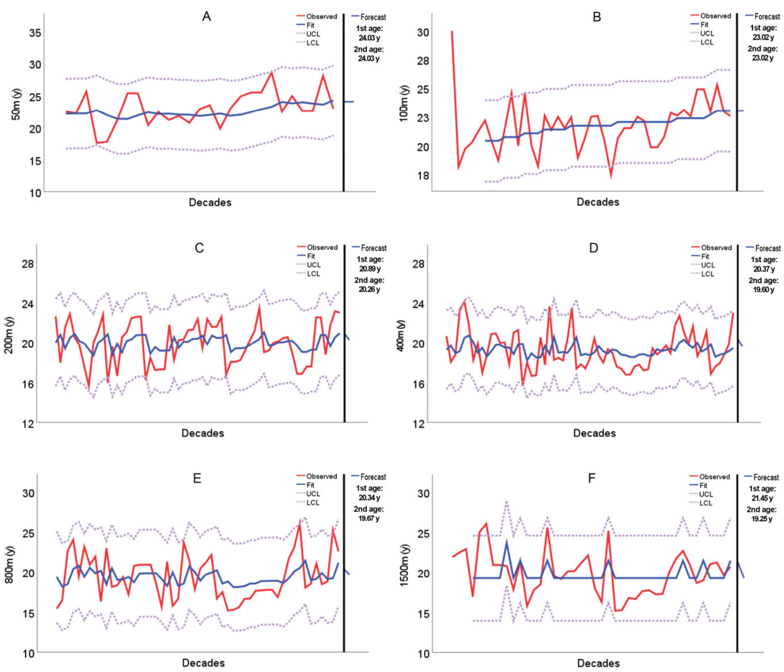

Figure 3. Forecast models for predicting age of male world record holders in all freestyle events (panel (**A**), 50 m; panel (**B**), 100 m; panel (**C**), 200 m; panel (**D**), 400 m; panel (**E**), 800 m; panel (**F**), 1500 m). Fit: line of best fit; UCL: upper confidence limit; LCL: lower confidence limit.

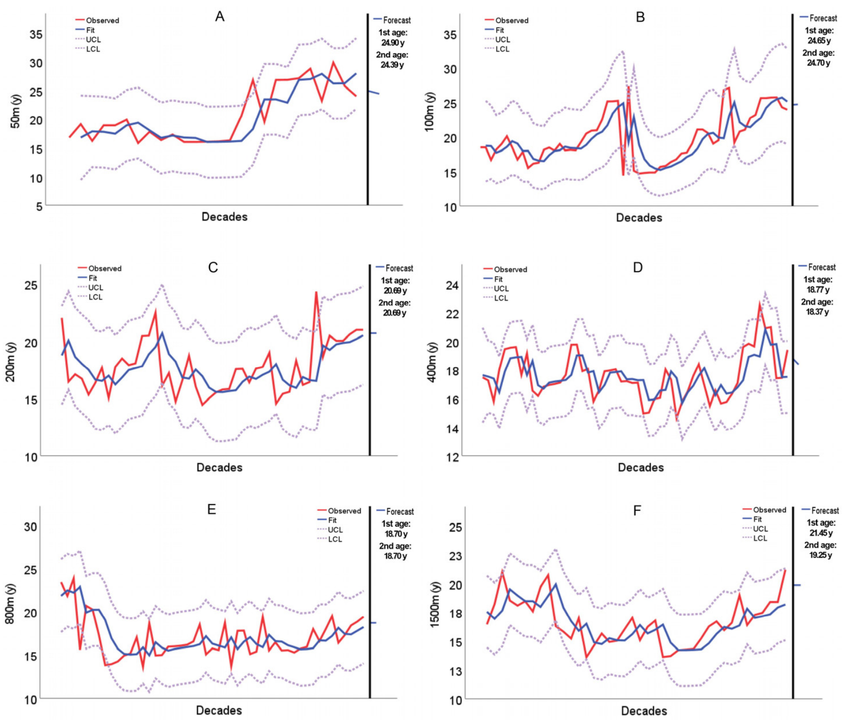

Figure 4. Forecast models for predicting age of female world record holders in freestyle events (panel (**A**), 50 m; panel (**B**), 100 m; panel (**C**), 200 m; panel (**D**), 400 m; panel (**E**), 800 m; panel (**F**), 1500 m). Fit: line of best fit; UCL: upper confidence limit; LCL: lower confidence limit.

4. Discussion

This study aimed to perform an analysis of historical data on swimming world records and the age of world record holders to identify trends and predict future events. There was a natural trend of improvement in WRs over the decades, with world record holders becoming older mainly in short-distance events. The future observations show a continuing improvement in WRs, with general stabilization in the age of world record holders but with a slight decrease in the age of males in long-distance events.

The retrospective analysis of WR evolution revealed a natural trend of improvement over the decades, consistent with broader trends seen in other sports [19]. The advancements in science and technology, such as better swimwear, training equipment, and monitoring devices, have enabled athletes to push the boundaries of their capabilities. Beyond technological support, swimming has become more multidisciplinary with technical teams being more complete, higher in number, and more specialized in the different aspects of performance. Over the years, swimmers have had access to more sophisticated training programs, personalized nutrition or recovery plans, and in-depth analysis of racing strategies [20], all of which contributed to enhanced performance and record-breaking achievements.

The growth of swimming as a sport has also led to increased participation and competition at both the elite and grassroots levels (e.g., as seen in the Michael Phelps effect). Greater competition at younger ages often drives athletes to train harder and strive for excellence, leading to improvements in performance at an adult age [21]. The changes in the sport itself by the periodic amendments to the rules and regulations governing swimming competitions may also have influenced WR evolution. For example, changes in pool design, including deeper, deck-level pools, and more effective anti-wave lane ropes [22] and starting blocks [23], have impacted swimming performances and contributed to the progression of WRs over time. These changes have made the sport more complete and up-to-date and have triggered the globalization of swimming to another level, exposing athletes to different coaching philosophies and competition styles from around the world. This exchange of knowledge and expertise drives innovation and improvement in swimming performance on a global scale.

The analysis of WRs revealed a notable trend in record frequency over the past few decades. Specifically, it was observed that between 1960 and 2010, there was a consistent increase in the frequency of world records being broken, which is in agreement with previous studies [24]. It is plausible that the significant improvements in swimming technology, evaluation techniques, and training processes during the mid- to late 20th century, as well as the scientific development in swimming suit design up to 2010, led to more rapid advancements and thus a higher frequency of record breaking. The beginning of the 21st century, mainly between the 2004 Athens Olympic Games and the 2009 Rome World Championships, represented the "shiny-suit era", with a large number of WRs being broken. However, it has been over a decade since FINA (nowadays World Aquatics) banned full-body tech suits, which can help explain the slowdown in the rate of world record breaking in the last couple of years.

Contrary to this trend in WRs, there was a nuanced pattern observed in the age of world record holders over the decades. Previous analyses of Olympic swimming data showed that the age of peak performance has remained remarkably consistent until later in the 1980s [25]. However, this trend changed between 1992 and 2013, with the Olympic finalists being remarkably older than in previous editions [26]. The dual career initiative in sport (which comprises the successful combination of education, training, or work with sport) can be an explanatory factor for swimmers peaking later in their careers [27]. This may also be dependent on the characteristics of each event (short-distance or long-distance). While for short-distance events there was a trend of an increase in the age of world record holders over the decades, an unchanged trend was found for long-distance ones. The consistent trend of swimmers achieving world records at older ages in short-distance events may be attributed to the requirements of the effort. These events typically rely heavily on explosive speed and power, which can be maintained or even improved with age through targeted training and experience [28]. The continued development of race strategy details [29], along with the improvement in novel recovery approaches or medical support [30], help older swimmers to extend their competitive careers and continue setting records at older ages. In contrast, the variations observed in the age of world record holders in long-distance events may reflect the unique physiological demands of these races. Long-distance events require a combination of endurance, aerobic capacity, and race-pacing maintenance [31], which may peak at an earlier stage of an athlete's career. Younger athletes may have a natural advantage in terms of aerobic capacity and recovery ability, allowing them to excel in longer-distance events more easily than their older counterparts [32].

Forecasting models of WRs (Figures 1 and 2) show promising evolution over the next decade (during the 2020–2029 period). As an example, predicted WRs for the 100 m freestyle event are 46.79 s and 46.69 s within the next few years. Three male WRs have already been broken within this time frame (e.g., David Popovici clocking 46.86 s in the 2022 European Aquatics Championships in Rome, Pan Zhanle clocking 46.80 s and 46.40 s in the 2024 World Aquatics Championships in Doha and in the Paris 2024 Olympics, respectively). This means that our models are fair and acceptable, and it should not be expected that swimming WRs will plateau so soon as previously reported by Nevill et al. [24]. There have already been 20 individual WRs (11 male and 9 female) in long-course events within this decade. Although there is a consensus that swimmers at this stage have already reached their physiological limits [33], there seems to be some room for improvement for further advancements in swimming performance. Considering the projections for the winning time in the Paris 2024 Olympics [34], it was not expected that any WR would be broken. Still, a fair number of WRs in freestyle events were achieved (two male WRs) and were somewhat in agreement with what our forecasts showed.

Forecasting models related to the age of record holders (Figures 3 and 4) showed us a mixed path. General stabilization in the age of world record holders in most of the freestyle events should be expected in the upcoming years. Stabilization in the age of male and female elite freestyle swimmers was seen between 1994 and 2016. Contrarily, Konig et al. [26] found an increase in the age of swimmers across World Championships and Olympic Games finals in a 20-year time frame (from 1992 to 2013). Although this might be a phenomenon with a random fluctuation, the age of a world record holder may sometimes not be within the age interval of those participating in the finals of great events. Some recent great performances were achieved by phenomenal teenage individuals like Summer McIntosh (15 years) and David Popovici (17 years). At the time of breaking the WRs, those swimmers were far from the 2016 average age (~23 years) of freestyle world-class swimmers [35]. So, this seems to be a random phenomenon with a nuanced pattern that opens space for outlier emergence that may counteract some forecast results. The existence of outliers is a well-known phenomenon that should be embraced by those who regularly work on sports prediction statistics [36]. As such, any future observations in this case should be interpreted with caution.

This study contributes valuable insights into the world records and age dynamics (e.g., career peak) for world-class swimmers. Coaches should be aware that there are sex-specific and event-specific dynamics in evolving trends over the decades. Understanding these trends can have implications for talent identification and long-term development of performance. This can also drive political strategies to keep the most talented swimmers close to the sport so that they can have a more sustainable career. The forecasting approach can also be seen as a powerful tool that can help us understand the potential performance and age limits for future world record breaking.

Some limitations and/or key aspects should be considered in upcoming research: (i) The included WRs were restricted to freestyle events. As such, a deeper analysis should be performed considering the progression of WRs in the remaining swimming events/techniques. (ii) Only WRs in the long-course pool were extracted, which leaves doubt as to whether the same trend would occur when WRs in the short-course pool are considered. (iii) Only broader trends about world records were shown, which suggests that future studies could delve into interdecadal analysis.

5. Conclusions

It can be concluded that a natural trend of improvement in WRs over the decades happened in long-course freestyle events, with world record holders becoming older mainly in short-distance events. The technology and training advancements played a key role here. In the upcoming years, WRs will improve, with distinct patterns being displayed in the age of world record holders depending on the competitive event. The age of male world record holders will stabilize in shorter events and decrease in longer distance ones, while for females, general stabilization should be expected for the majority of the competitive events.

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