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Marion Guillaume [1], Stephane Len [1], Muriel Tafflet [1,2], Laurent Quinquis [1], Bernard Montalvan [3], Karine Schaal [1], Hala Nassif [1,4], François Denis Desgorces [1,4], and Jean-François Toussaint [1,4,5]

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1 IRMES (Institute for biomedical and epidemiological research in sport), INSEP (National Institute of Sports Expertise and Performance), 11 avenue du Tremblay, 75012 Paris, France

2 INSERM (National Institute of Health and Medical Research) unit 970, 56 rue Leblanc, 75015 Paris, France

3 FFT: French Tennis Federation, 2 avenue Gordon Bennett, 75016 Paris, France

4 Paris-Descartes University, 12 rue de l'école de médecine, 75006 Paris, France

5 CIMS (Center for Sports Medicine Research), Hôtel-Dieu, Publics Assistance Paris Hospitals of Paris, 1 Parvis Notre Dame, 75004 Paris, France

Contact information

Marion GUILLAUME 11, avenue du Tremblay 75012 Paris

Tel: +33141744129; Fax: +33141744175; e-mail:irmes@insep.fr

ABSTRACT

Introduction: The victory percentages for tennis players who entered the Top 10 Women and Men rankings show various evolutions related to age and time since 1968.

Methods: The study analysed the careers of all Top 10 players: 97 women (50,933 matches) and 144 men (92,450 matches). For each player, we describe a biphasic performance course. Two generations were compared: the first one (G1), including players who started their professional career before 1985; the second one (G2), with players starting after 1985.

Results: The average career length is 16.1±3.8 years for the Top 10 men and 15.8±4.4 for women. Compared to G1 players, G2 players begin earlier (Women: 1.3 year, Men: 0.8 year), but career length remains the same. An exponential model describes the time course of the victory percentage with a great similarity for both genders. Using this equation, the peak victory rate reaches 82.5% at 21.5 years for No.1 women and 78.5% at 23.7 years for No.1 men, showing a greater precocity and earlier decline in women. Finally, the area under the curve shows a potential that is 22.8% (Men) to 56.8% (Women) larger for the No.1 players as compared to all other No.2 to No.10.

Conclusion: Tennis players in the Top 10 show a biphasic career. Women reach their highest level earlier than men, consistent with their more precocious biological development. For the current generation, the peak performance tends towards a younger age that the first generation. We show how to precisely quantify and compare tennis performances using indicators that follow the trends of development and aging, and demonstrate that precocity does not provide a larger victory potential.

Keywords: Physiology; Precocity; Peak Performance; Gender Gap; Generation Gap

Introduction

Since the beginning of Open era, the tournaments of the WTA (Women's Tennis Association) and ATP (Association of Tennis Professionals) have constantly produced tennis legends and mythical confrontations. "If you can meet with Triumph and Disaster and treat those two imposters just the same" (15) is written on the wall of the Centre Court players' entrance at Wimbledon. And in the July 2008 Wimbledon final, Rafael Nadal defeated Roger Federer in his garden, before becoming No.1. He was 22 years old and in full upward progression, while Roger Federer at 27 began to show slight signs of performance decline.

This most recent transfer of power illustrated that tennis, as many other disciplines, obeys a law of progression and regression (7, 18, 22), that No.1 players successively experience. The cycle begins with the first professional match, shows a progression, which reflects the development of the player's capabilities until a peak is reached. Then performances start to slowly decrease over the years until the player chooses to quit. However, the exact evolution of a tennis career results from the expression of several events: among them, the date of entrance on the professional circuit, the prevalence of injury (24), and age at retirement. It could also depend on unknown predisposition, training volume, technical development and media coverage, which may have introduced differences between generations (12, 25). Intensive training at a young age can lead to a higher prevalence of injury (4). Lastly, the McCann Precocity-Longevity hypothesis states that "that those who reach career peaks earlier tend to have shorter lives" (19), suggesting that the effects of an early success may act negatively on long term health parameters (1, 20) and it incites us to question the early recruitment of the new players' generation and measure its impact.

Previous studies have highlighted the impact of age on human physical capacities and have sought to determine the optimum age for certain human biological functions (3, 16, 26), or activities such as athletics or swimming (7, 22, 25, 28). Some studies showed a common physiological pattern of growth and decline (7, 18, 22). In this study, we analyze a large pool of tennis players and show a similar time course common to a majority of players, using a new indicator: the percentage of matches won relative to age. Athletes' ranking have also been used as an indicator of performance (12, 25), but the point systems of ATP and WTA have evolved several times since 1968 (5, 14, 32). The victory percentage is more stable and

remains consistent during the whole Open era. Furthermore, a player may remain in the ranking, while he reduces his physical investment – *i.e.* the physical number of yearly played matches. The point systems do not offer as much precision as the yearly victory percentage.

Our aim is to model the tennis performance career as a function of age, to measure the potential of each player, their successes and highlights all the mechanisms involved in a sport career that are crucial determinants of longevity on the circuit. Thus, we also question whether the Precocity-Longevity hypothesis may be observed at the level of the players' career length by comparing two generations and if the precocity of a player may increase its tennis potential.

Materials and Methods

Data

Paragraph Number 5 All players included were featured in the Top 10 WTA or ATP ranking between 1973 and 2009. Our study analyses all 50,933 matches played by the 97 Women (W) players and all 92,450 matches played by the 144 Men (M) players between 1968 and 2009 (5, 14, 32). Matches played during Davis Cup, Fed Cup, Olympic Games, Grand Slam Cup, and World Team Cup are not included, as these tournaments do not affect the ATP or WTA rankings (or only until recently, and others do not occur annually).

Tennis players are divided into 2 generations in order to compare their career parameters and performances: first generation (G1) with a first match played before and in 1985 (nW=47 and nM=69 for women and men respectively) and second generation (G2) with a first match played after 1985 (nW=50 and nM=75). For a homogeneous number of players by generation, 1985 has been chosen the median year.

Variables

The following variables are collected from WTA, ATP and ITF website (5, 14, 22) for each player: gender, best ranking, birth year, age of career start and retirement; for each match, the year and the result for the player (victory or defeat). The following variables are defined for each player: generation, length of career, age and number of matches played per year.

Beginning, retirement and length of career

The length of career has been considered for all players, except for the ones still active in the WTA or ATP Tour. The average longevity, the average age at the career beginning and retirement have been calculated for all players and for the two generations. The bilateral T-test was used to compare the difference of mean between genders and between generations. Statistical significance was set at $p<0.05$.

Descriptive Analysis

· Number of matches per age are measured for each player: $matchp,t$ with p the player and t the age. The mean number of matches per athlete for each age has been calculated for women (*Wmatcht*) and men (*Mmatcht*) respectively where t is the age.

· The number of victories is measured by age for each player: $victoryp,t$, with p the player , and t the age. The victory percentage (%$victoryp,t$) is defined as the annual ratio of victory over the total of matches played by player p at age t: $\%victoryp,t= victoryp,t/matchp,t$

· The logarithmic correlation between the number of matches played and the victory percentage is calculated.

Fitted victory percentage

An exponential model is chosen to fit the age victory percentages for each player (7, 18, 22): $\%victoryp= ap[1-exp(bptp)]+cp[1-exp(dptp)]$ tp is the age for the player p. The coefficients ap, bp, cp and dp are estimated by the method of least-squares.

Modelled Curves

· The mean of individual coefficients ap, bp, cp and dp is calculated for the Top 10 W and M players. Modelled curves are displayed using the obtained mean coefficients. The coefficients are then stratified by gender and generation. In addition, the modelled curves No.1 women and men and the modelled curves at No.2 to No. 10 are calculated.

· For each curve the area under the curve (AUC) is calculated, as well as the age and value at the performance peak. A bilateral T-test is used to compare the difference of AUC mean between generations. Statistical significance is set at $p<0.05$.

Ethics

The data collected for this study are obtained from ATP, WTA and ITF public websites. This study therefore used a research protocol qualified as non-interventional, in which *"…all acts are performed in a normal manner, without any supplemental or unusual procedure of diagnosis or monitoring."* (article L1121-1 of the French public health code). According to the law, its approval therefore did not fall under the responsibility of a committee for the protection of persons (CPP). For these reasons, it is not necessary to obtain informed consent from the athletes evaluated. This study is designed and monitored by the IRMES (Institut de Recherche bioMédicale et Epidémiologique du Sport) scientific committee.

Results

Beginning, Retirement and length of Career

The mean career duration is 15.8 ± 4.4 years for all women and 16.1 ± 3.9 years for all men, respectively. For men, the career duration of G1 players is 16.8 ± 4.3 years; the G2 mean is 14.7 ± 2.5 years (Table 1), a significant 2.1 years reduction.

At their first match, players were 15.9 ± 1.7 (W) and 17.5 ± 1.7 years old (M) (Table 1) respectively. For G1, the age at first match was 16.5 ± 1.9 years for women and 17.9 ± 1.9 years for men. It is 15.2 ± 1.3 years (W) and 17.1 ± 1.3 years (M) for the present generation (Table 1).

The age at retirement is 31.0 ± 4.3 years (W) and 32.8 ± 4.1 years (M). For men, it was 33.6 ± 4.4 years before 1985; it is 31.2 ± 2.5 years after 1985. For G2 players, age at the last match is now 2.4 years earlier than for G1 (Table 1). All results and significance are described in Table 1.

Descriptive Analysis

The average number of matches played per age follows a progression cycle, which increases and decreases with a peak of 49.2 ± 22.7 matches at 23 years for women, and 60.2 ± 19.4 matches at 24 years for men (Figure 1A).

The average victory percentage per age follows a similar progression cycle with a peak of 66.7 ± 12.8% at 23 years old for women. For men this peak reaches 66.6 ± 11.2% at 24 years old (Figure 1B).

The average total number of matches during the careers of Top 10 women and men is 529.2 ± 262.1 and 674.0 ± 224.2 respectively.

Victory percentage and number of played matches show a logarithmic correlation: $y = 0.128 \ln(x) + 0.188$ for Top 10 women players (Figure 2), $y = 0.150 \ln(x) + 0.061$ for Top 10 men. Analyzing these results for each rank shows similar correlations.

Fitted victory percentage

The fits show two phases of growth and decline. Such a cycle is common to all players (Figure 3). For women, the fitted victory percentage of Top 10 rises to 69.7% at 21.5 years of age (Figure 4). For the No.1 players, it only augments to 82.5% at the same age: 21.5 years (Table 1).

For men, the modelled victory percentage of Top 10 rises to 69.4% at 24.1 years (Figure 4). For the No.1 players, it increases to 78.5% at 23.7 years of age (Table 1). For the Top 10 players, women start and retire earlier than men (Figure 4), but have a similar AUC.

For women, the victory peak occurs earlier for all No.1 players compared to all others (No.2 to No.10): 21.5 years *vs.* 22.7 years. The AUC for No.1 is 56.8% greater (AUCNo.1 = 13.8; AUCNo.2 to No.10 = 8.8) (Table 1). For men, the same comparison shows that the peak also occurs earlier for all No.1 (23.7 years *vs.* 24.2 years for No.2 to No.10). The men's No.1 AUC is also greater (AUCNo.1 = 11.3; AUCNo.2 to No.10 = 9.2) (Table 1), a 22.8% increase.

Generations

For women, the fit of the G1 Top 10 victory percentage shows a peak of 68.1% at 23.5 years. For G2 it increases up to 71.3% of wins at 21.5 years. The players' AUCs are not significantly different between G1 and G2 (8.7 *vs.* 10.7) (Table 1).

For men, the fitted curve of the G1 Top 10 shows a peak of 71.7% at 25.0 years. For G2 it decreases to 67.4% at 23.3 years. The AUCs of the players of the first generation are not

different (AUCG1M = 9.2) than those of the second period (AUCG2M = 9.9) (Figure 5, Table 1).

Discussion

Our study is the first to analyze tennis performances through the yearly percentage of victories of all players who reached the Top 10 WTA and ATP rankings during their careers. Curves are fitted with an exponential model, describing lifetime performance course (7, 18, 22). This model allows for the comparison of the different progression phases between individual players, between women and men, and between successive generations.

The curves describe an athlete's career (Figure 3), with two phases: rise and decline. As already observed (25) the comparison between genders shows that women parameters are earlier than men ones but with a similar AUC (Figure 4). The model also highlights the greater investment of the second generation (Figure 5) (12, 25). Furthermore, the logarithmic correlation found between the number of matches played by season and the victory percentage shows the constant reciprocity between quantity and quality (Figure 2). These results are coherent for men and women. Previous studies analyzed quantifiable disciplines (Cycling, Swimming, Track and Field, Weightlifting) and used world records as indicators of performance (7, 8-11, 13, 30), but tennis does not provide a precise performance indicator. Other studies have looked at the maximum performance according to age for baseball (27) or tennis (17), highlighting a link between advanced age and reduced performance. In this study, we propose a new indicator to assess the players' progression: the percentage of matches won depending on age (Figure 1B). This parameter allows for the determination of progression cycle during the career.

Tennis capital

Among best players, the length of a career (Table 1) is already a clear indicator of success, but the area under the curve (AUC) (Table 1) describes their full potential - their energy investment: physical and mental - as compared to all other opponents of their generation (Table 1) (25). This value is a temporal measure (expressed in %.year) and can be considered

as a player's "tennis capital". For example, Björn Borg is 12.3, Pete Sampras is 12.6 (Figure 3), Ivan Lendl: 13.6, John McEnroe is 14.3, and André Agassi 17.5; Monica Seles is 14.3, Stefanie Graf 17.0 (Figure 3), Chris Evert is 20.3, and Martina Navratilova 24.9.

The best player, No.1, usually starts earlier than other players. The age at peak tennis performance also occurs earlier for No.1 as compared to all others and their AUC is much larger (Table 1). These differences help to characterize their exceptional career.

The career of a tennis player follows a law of progression and regression (7, 18, 22). It begins at the entrance on the professional circuit, grows rapidly until the peak, and then decreases slowly. While the majority of careers respect the form of a parabola, few careers present discontinuities that may be associated with injuries, pregnancy, any other career break, such as temporary exclusion for positive doping control. In several sport populations, the optimum age for performance is reached at 25 years (12, 18, 22, 25); the optimal age for tennis performance appears to occur slightly earlier (25) (Table 1). However, this peak age has shifted between G1 and G2 (Figure 5, Table 1). In the second generation, the performance peak occurs at an earlier age, while the length of career is reduced. What may be the impact of such a change on the physical and mental potential of players (1, 2)?

Precocity-Longevity

McCann (19) suggested that peak performance at an early age may be characterized by a high stress resulting in a decrease in life longevity. Abel and Kruger (1) confirmed this hypothesis on the Major League Baseball players, and highlighted some factors: the importance of psychological stress on too young players, the media attention and the expectations of entourage about their performances.

A player's "tennis capital" represents the exact performance during his career. However too large and too early investment may reduce total career longevity. The intensive practice at a young age may in fact reduce the physical potential of a player, and increase his or her injury prevalence (4). Many players have not been able to return to high level competition after injury (31) and have thus ended their careers. These results may also question the earliness and the link between the presence of very young players on the professional circuits and the length of their careers. Rafael Nadal for instance shows great precocity. Considering the mean AUC of all No.1 before him, this precocity could limit the duration of his career. The coming

years will show what impact, this early quest for performance may have on his health and overall tennis potential.

To better understand the involved mechanisms in the career duration, we calculated the tennis capital through the AUC of the victory percentage curve, and tested the precocity hypothesis. The analysis of the two generations shows that an earlier start is in fact associated with an earlier retirement and with no increase of the tennis potential.

Gender differences

The rates of biological development differ for men and women (6, 25, 29). Modeling the progression of the Top 10 women and men reflects these differences in growth between genders (Figure 4). The length of career and AUC show that the tennis potential of the Top 10 women and men are similar (Table 1). The gender gap in both the age at first match and age at peak (Table 1) is most probably due to differences in maturity (6, 25, 29). As opposed to quantifiable disciplines (30), the No.1 women's capital seems greater than the men's one. Hypotheses can be raised: competition in the male professional circuit may be more intense (23). The number of players in the ATP and WTA tour registered over the same period (144 M versus 97 W) sustains this hypothesis as well as the mean number of match played throughout the careers. However, technique, power and game length are different for men and women; women's tennis then could be less physically demanding.

Generation Gap

The professionalization of tennis has partially changed the game and its techniques (12, 25). We therefore distinguished two generations of players. The second generation women and men started their professional career at a younger age than the first players possibly due to new tennis academies and a higher investment in very young players (4, 12, 22). In G2, women and men both reach their performance peak and end their careers earlier than those in G1 (Table 1, Figure 5). Competition also intensified during the Open era. Even though the evolution of the athletes' technical and physical qualities and the economical impact on the sport have altered some parameters of professional tennis careers, this did not result in a significant change of their "tennis capital".

For a similar victory percentage, the number of matches played may differ between players and thereby create a bias. Some players included in the database have started their career

before the start of the Open era; others have not yet finished their career reducing the "precision" of some fits. However the increase in the number of matches played by age follows the same progression cycle (Figure 1).

Conclusion

Paragraph Number 37 Tennis is a precisely quantifiable sport allowing for comparison between gender, generation and best players, using an appropriate indicator: the percentage of won matches. This analysis shows the same performance progression as compared to disciplines with world records. Applied to Top 10 players, this indicator shows a physiological cycle of growth and decline. An improved understanding of the career time course may help coaches and physicians to plan skills training more appropriately, the expected gain for each age, and to better anticipate or respond to injury. Despite a greater precocity, the capital of tennis players did not evolve during the professional period. This indicator might be applicable to all individual sports of confrontation.

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Author Contributions

Designed research: MG, SL, JFT. Performed research: MG, SL, MT, JFT. Analyzed data: MG, SL, MT, LQ, BM, KS, HN, FDD. Wrote the paper: MG, JFT.

Conflict of interest: We declare that we have no conflict of interest.

Role of the funding source: The sponsor had no role in the study design, data gathering, data analysis, data interpretation, or writing of this report. The corresponding author had full access to all data in the study and had final responsibility for the decision to submit for publication.

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Figure Legends

Figure 1. Relation between age and performance for the Top 10 men over 20 years:

A. Yearly average number of matches played according to age.

B. Yearly average victory percentage according to age. The peak is at 24 years with 66.7% of victory for 49.2 matches.

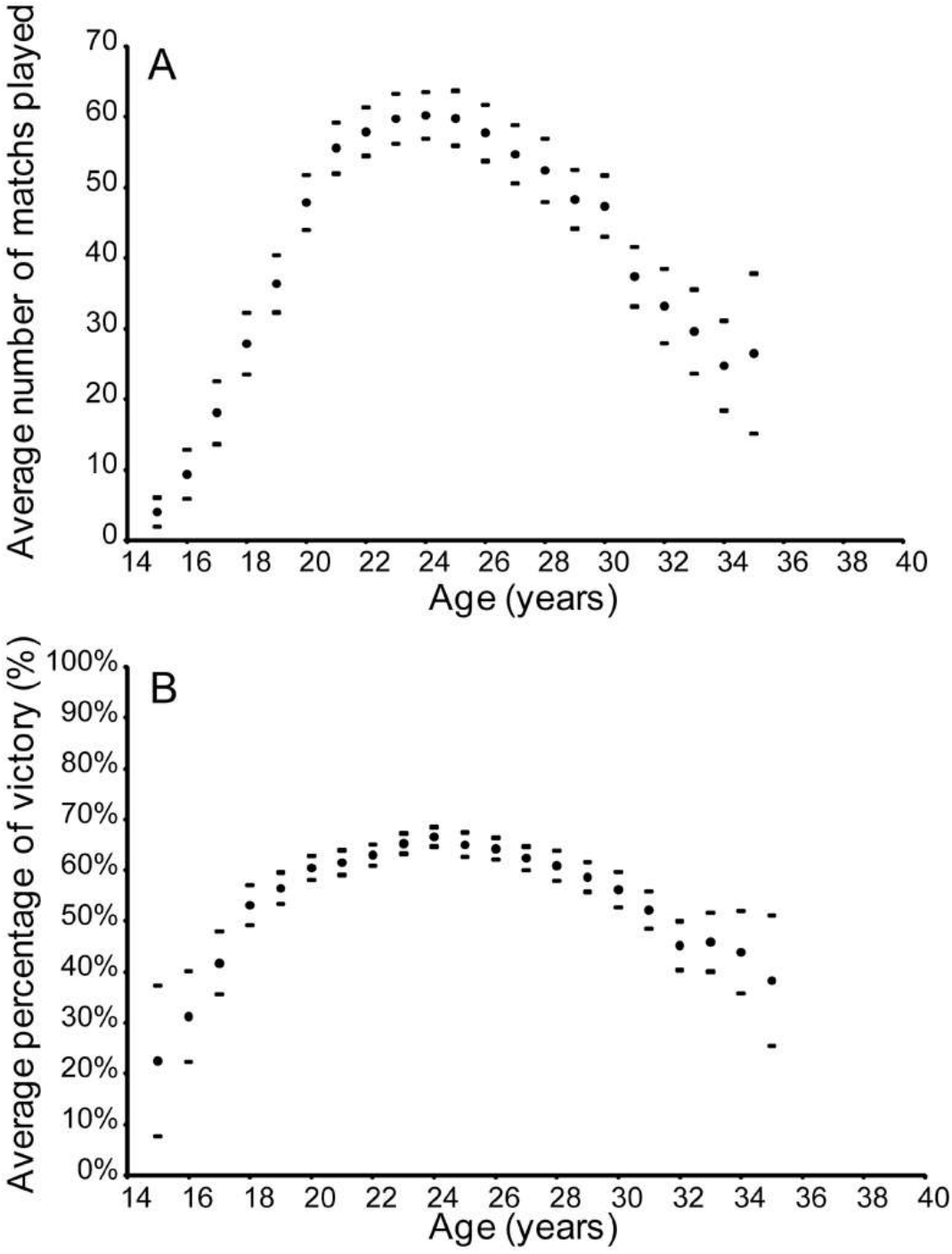

Figure 2. Relation between played matches and victory percentage for the Top 10 female:

Logarithmic correlation: *0.1281ln(x)+0.1882*, R2=0.72. The more you play, the more you win.

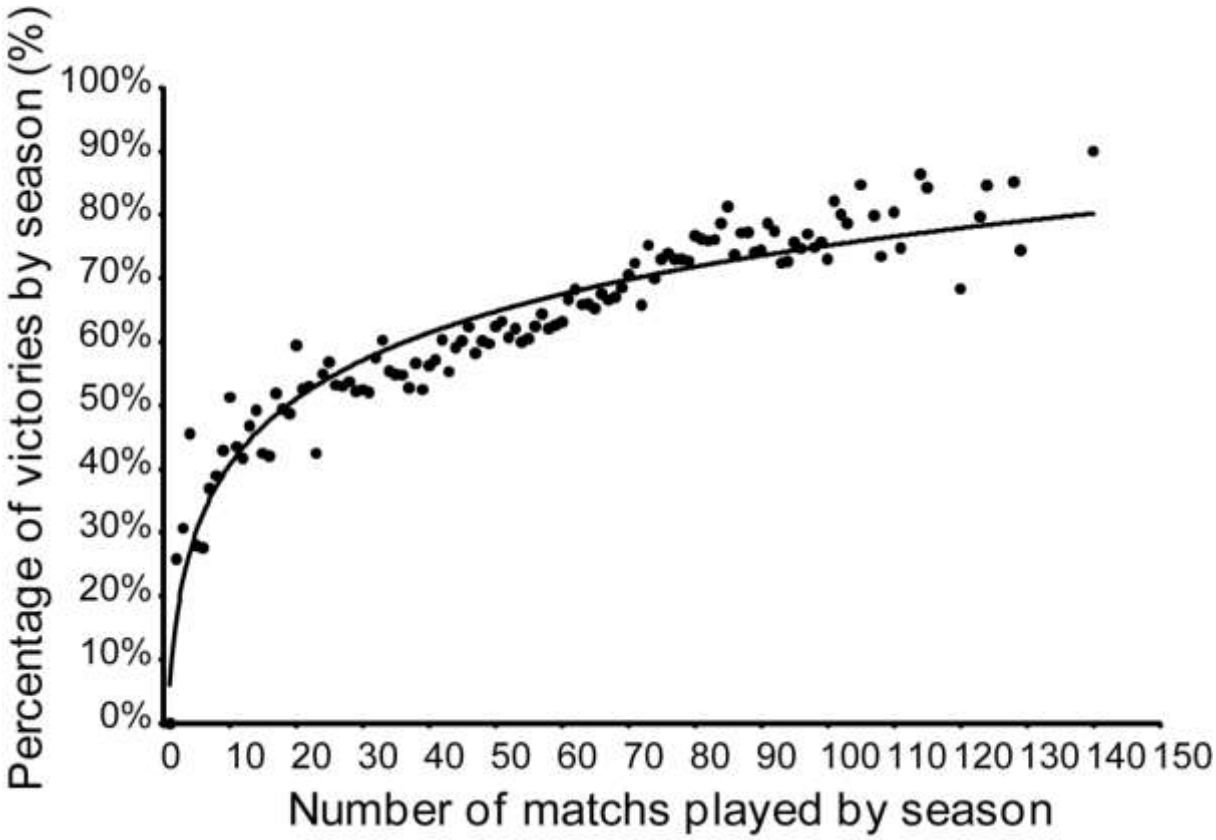

Figure 3. Model fitting for two players: Stefanie Graf (No.1 women, 1987-1997) reaches her peak at 19.8 years with 94.8% of victory and Pete Sampras (No.1 men, 1993-1998) reaches his peak at 23.6 years with 85.0% of victory. Both fitted peaks coincide the exact value of 97.6% and 89.8% at age 20 and 23 respectively.

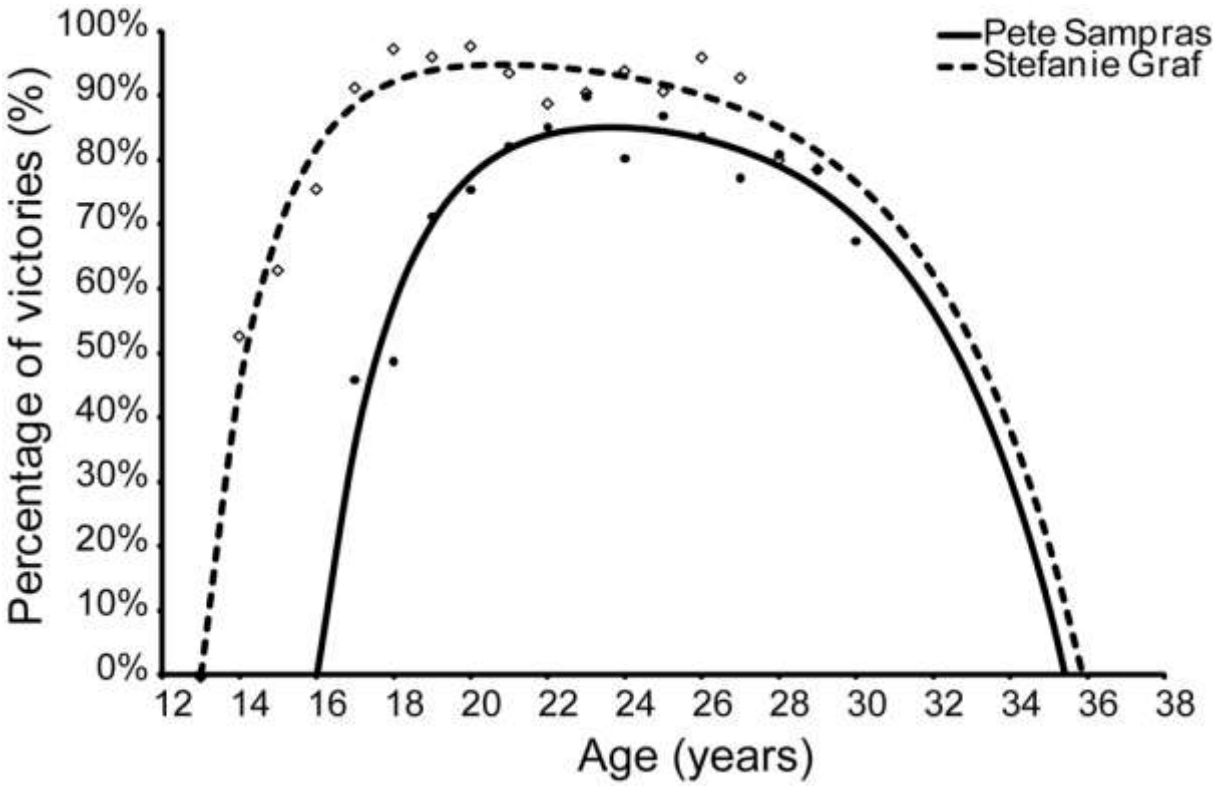

Figure 4. Modeling for Top 10 and No.1 by gender. A. Top 10 Women and Men. Women reach their peak at 21.5 years with 69.8% of victory and an AUC of 9.7. Men reach their peak at 24.1 years with 69.4% of victory and an AUC of 9.6. Women and men have the same tennis capital. **B. No.1 Women and Men.** Women reach their peak at 21.5 years with 82.5% of victory and an AUC of 13.8. Men reach their peak at 23.7 years with 78.5% of victory and an AUC of 11.3.

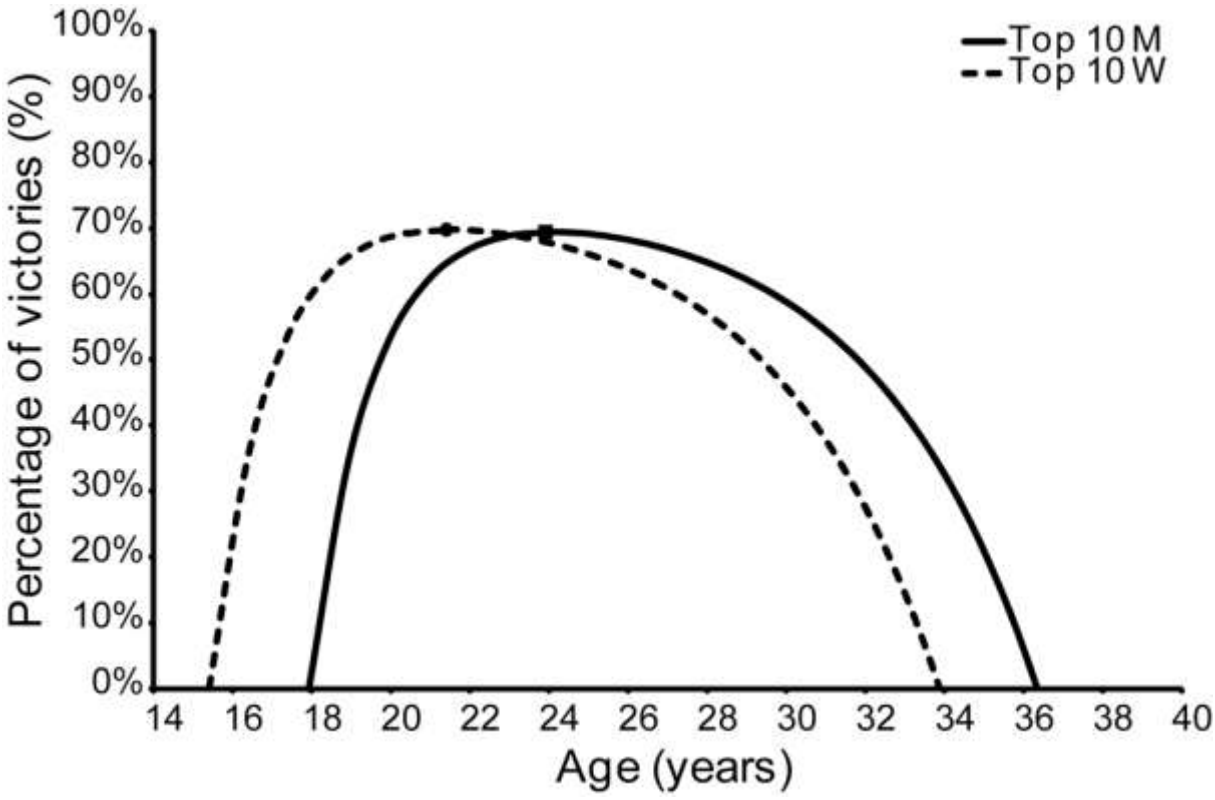

Figure 5. Parameters for generation G1 and G2 for the Top 10 men.

G1 players reach their peak at 25.0 years with 71.7% of victory and an AUC of 9.2. G2 players reach their peak at 23.3 years with 67.4% of victory and an AUC of 9.9. The difference of an AUC mean is not significant (p=0.199).

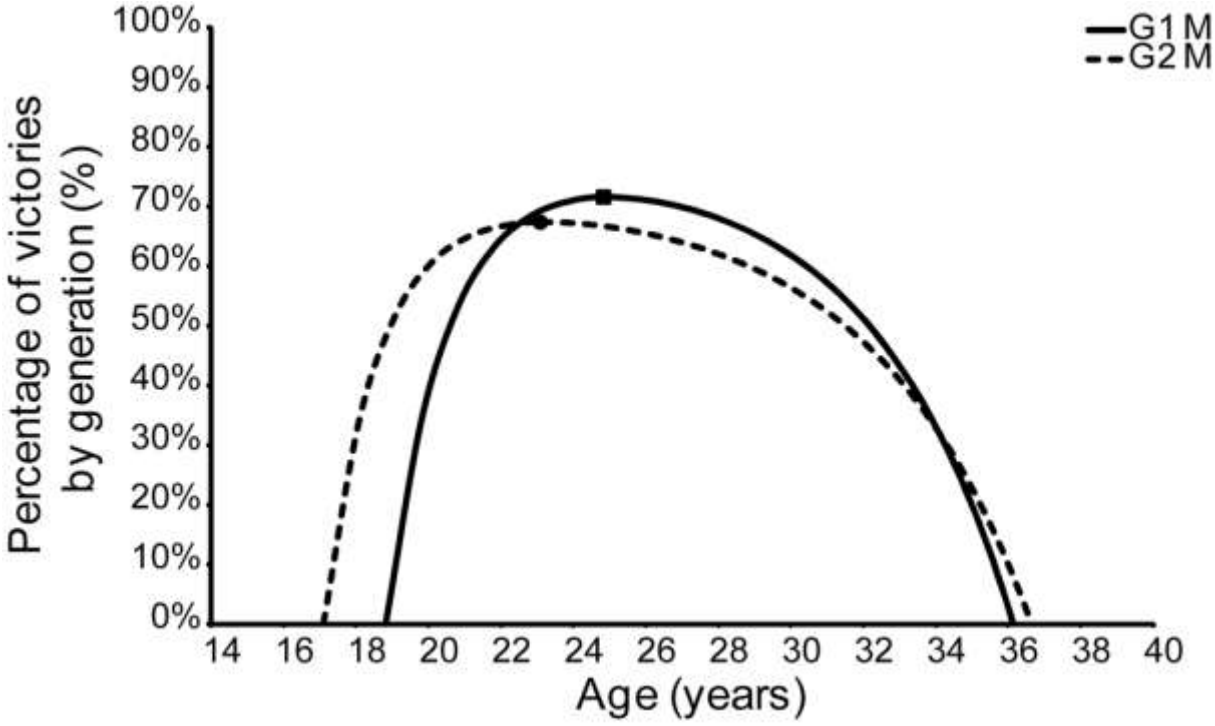

Table 1. Parameters of career and modelling.

	Gender (Year)	**Women** **Mean +/- SD**	**Men** **Mean +/- SD**	**Gender gap**	**Significance** **p<0.05**
	First Match	15.87 +/- 1.71	17.47 +/- 1.66	1.60	*
	Last Match	30.99 +/- 4.83	32.84 +/-4.05	1.85	*
	Length Career	15.76 +/- 4.42	16.07 +/- 3.90	0.31	
	Generation (Year)	**G1** **Mean +/- SD**	**G2** **Mean +/- SD**	**Generation gap**	**Significance** **p<0.05**
Women					
	First Match	16.53 +/- 1.85	15.24 +/- 1.29	1.29	*****
	Last Match	31.43 +/- 5.42	30.22 +/- 3.56	1.21	
	Length Career	15.89 +/- 5.02	15.52 +/- 3.19	0.37	
Men					
	First Match	17.88 +/- 1.90	17.09 +/- 1.32	0.79	*
	Last Match	33.64 +/- 4.43	31.24 +/- 2.50	2.40	*
	Length Career	16.75 +/-4.26	14.68 +/-2.54	2.07	*
	Modelling	**N°1**	**N°2 to N°10**	**G1**	**G2**
Women					
	Optimum age (year)	21.5	22.7	23.5	21.5
	Victory percentage peak (%)	82.5	66.6	68.1	71.3
	AUC (%.year)	13.8	8.8	8.7	10.7
Men					
	Optimum age (year)	23.7	24.2	25	23.3
	Victory percentage peak (%)	78.5	67.6	71.7	67.4
	AUC (%.year)	11.3	9.2	9.2	9.9

The mean age and standard deviation at first match, at last match and career length are calculated by gender and generation and showing earlier potential in women and shorter career length in G2 men who are more precocious. The optimum age, the maximum victory percentage and AUC are calculated by gender and generation and showing higher values for No.1 as compared to No.2-No.10 and earlier optimum age for current G2 players.