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Audrey Difernand

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Université Paris Cité

Ecole doctorale « Sciences du Sport, de la Motricité et du Mouvement Humain » (ED 566)

Institut de Recherche bio-Médicale et d'Epidémiologie du Sport – IRMES (EA 7329)

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en vue de l'obtention du grade de Docteur

Estimation of potentials among young athletes

Présentée par Audrey Difernand

Dirigée par Jean-François Toussaint et Adrien Sedeaud

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Composition du jury:

Pascale DUCHE	<i>Rapportrice</i>	Professeure, Université de Toulon
Sébastien RATEL	<i>Rapporteur</i>	Maître de Conférences, HDR, Université Clermont-Auvergne
Felien LAUREYS	<i>Examinatrice</i>	PhD, Ghent University
Olivier MAURELLI	<i>Examineur</i>	Maître de Conférences, Université de Montpellier
Jacques PRIOUX	<i>Examineur</i>	Professeur, ENS Rennes
Nikki ROMMERS	<i>Examinatrice</i>	PhD, University of Basel
Jean-François TOUSSAINT	<i>Directeur</i>	PU-PH, Université Paris Cité
Adrien SEDEAUD	<i>Co-directeur</i>	Chercheur, HDR, Université Paris Cité



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Presented by Audrey Difernand

Supervised by Jean-François Toussaint and Adrien Sedeaud

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Jean-François TOUSSAINT	<i>Directeur</i>	PU-PH, Université Paris Cité
Adrien SEDEAUD	<i>Co-directeur</i>	Chercheur, HDR, Université Paris Cité

ABSTRACT

Sports among young individuals are a fundamental aspect of their physical, mental, and social development. It provides the opportunity to engage in physical activities, cultivate motor skills, build friendships, and inquire values such as discipline, perseverance, and fair play. Moreover, sports contribute to promote a healthy and active lifestyle from an early age, which can have positive long-term implications for health. However, youth sports also come with their set of challenges, including competition pressure, early specialization, and issues related to selection and inclusion. Therefore, it is essential to understand the various aspects of youth sports, consider the individual needs and aspirations of young athletes, and promote a balanced approach that encourages both sports performance and the overall well-being of young individuals. This thesis work revolves around age factors that develop and maximize the potential of young athletes while considering their performance uniqueness in a same-age category. Initially, despite athletes being grouped by age categories to ensure greater fairness, performance differences persist in swimming and athletics for all age categories between 10 and 16 years, both in girls and boys. However, it is possible to rebalance the performances for a better evaluation in relation to the athlete's age category. Nevertheless, disparities don't only exist in terms of performance. When considering dropouts among young swimmers, they are more likely to be affected by dropouts than their relatively older counterparts. We also examine the influence of gender and performance on youth athlete dropout rates. Girls tend to exit sports programs earlier and more frequently than boys, with dropout rates rising as performance levels decline. Furthermore, we highlight the role of maturity status in evaluating youth swimmers' performance. Swimmers who participate in more events and demonstrate greater maturity tend to outperform their peers with lower performance levels. Lastly, we analyze conversion rates from junior to senior categories in swimming. Succeeding in competitive swimming during youth does not necessarily guarantee future success. A better consideration of these factors would help reduce the impacts on dropout and conversion rates, ultimately leading to a more accurate estimation of an individual's sports potential.

Keywords: swimming, track-and-field, performance, age, relative age effect, maturation, dropout

RESUME

Le sport chez les jeunes individus est un aspect fondamental de leur développement physique, mental et social. Il offre l'opportunité de participer à des activités physiques, de développer des compétences motrices, de nouer des amitiés et d'acquérir des valeurs telles que la discipline, la persévérance et le fair-play. De plus, le sport contribue à promouvoir un mode de vie sain et actif dès le plus jeune âge, ce qui peut avoir des impacts positifs à long terme pour la santé. Cependant, le sport chez les jeunes comporte également son lot de défis, notamment la pression de la compétition, la spécialisation précoce et des problèmes liés à la sélection et à l'inclusion. Par conséquent, il est essentiel de comprendre les différents aspects du sport chez les jeunes, de prendre en compte les besoins individuels et les aspirations des jeunes athlètes, et de promouvoir une approche équilibrée qui encourage à la fois la performance sportive et le bien-être global des jeunes individus. Ce travail de thèse porte sur les facteurs liés à l'âge qui développent et maximisent le potentiel des jeunes athlètes tout en tenant compte de leur unicité de performance dans une même catégorie d'âge. Initialement, malgré le regroupement des athlètes par catégories d'âge pour garantir une plus grande équité, des différences de performance persistent en natation et en athlétisme pour toutes les catégories d'âge entre 10 et 16 ans, aussi bien chez les filles que chez les garçons. Cependant, il est possible de rééquilibrer les performances pour une meilleure évaluation par rapport à la catégorie d'âge de l'athlète. Néanmoins, les disparités ne se limitent pas seulement en termes de performance. Lorsque l'on considère les abandons parmi les jeunes nageurs, ils sont plus susceptibles d'être touchés par les abandons que leurs homologues relativement plus âgés. Nous examinons également l'influence du genre et de la performance sur les taux d'abandon des jeunes athlètes. Les filles ont tendance à arrêter la pratique de la natation plus tôt et plus fréquemment que les garçons, avec des taux d'abandon qui augmentent à mesure que les niveaux de performance diminuent. De plus, nous mettons en évidence le rôle de la maturation dans l'évaluation de la performance des jeunes nageurs. Ceux qui participent à plus d'épreuves et qui montrent une plus grande maturité ont tendance à surpasser leurs pairs ayant des niveaux de performance inférieurs. Enfin, nous analysons les taux de conversion des catégories juniors aux catégories seniors en natation. Il s'avère que la réussite en natation au niveau compétitif pendant la jeunesse ne garantit pas nécessairement un succès futur dans la

catégorie senior. Une meilleure prise en compte de ces facteurs contribuerait à réduire les impacts sur les taux d'abandon et de conversion, conduisant ainsi à une estimation plus précise du potentiel sportif individuel.

Mots-clés : natation, athlétisme, performance, age, effet d'âge relatif, maturation, abandon

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2. **Difernand A**, De Laroche Lambert Q, Pla R, Barlier K, Marc A, Ferri S, Dupas O, Antero J, Toussaint JF, Sedeaud A. Corrective adjustment methods for relative age effects on French young swimmers' performances. *PLoS One*. 2023 Apr 24;18(4):e0283229. doi: 10.1371/journal.pone.0283229. PMID: 37093823; PMCID: PMC10124878.
3. **Difernand A**, Mallet A, De Laroche Lambert Q, Pla R, Marc A, Barlier K, Antero J, Toussaint JF, Sedeaud A. Dropout among French swimmers: gender, relative age effect and performance level influences. *Journal of Sport Sciences*. Under review.
4. **Difernand A**, Mallet A, De Laroche Lambert Q, Pla R, Dernoncourt E, Marc A, Barlier K, Antero J, Toussaint JF, Sedeaud A. Biological maturity and performance in youth swimming. *Journal of science and medicine in sport*. Under review.
5. **Difernand A**, Brimont A, De Laroche Lambert Q, Pla R, Marc A, Barlier K, Antero J, Toussaint JF, Sedeaud A. Early specialization in competition in French swimming. *International journal of sports physiology and performance*. Under review.
6. De Laroche Lambert Q, **Difernand A**, Antero J, Sedeaud A, Toussaint JF, Pierre Yves L, Coulmy N. Relative age effect in French alpine skiing: Problem and solution. *Journal of Sports Science*. 2022 May;40(10):1137-1148. doi: 10.1080/02640414.2022.2052428. Epub 2022 Mar 24. PMID: 35321626.

7. De Laroche Lambert Q, Barlier K, Hamri I, **Difernand A**, Sedeaud A, Toussaint JF, Antero J, Louis PY, Coulmy N. Potential estimation model in French alpine skiing - Individual evolution curve and progression typology. *Frontiers in Physiology*. 2023 Jan 5;13:1082072. doi: 10.3389/fphys.2022.1082072. PMID: 36685191; PMCID: PMC9849383.

BOOK CHAPTERS

1. Sedeaud A, De Laroche Lambert Q, **Difernand A**, Marc A. « De la détection de performance vers l'estimation de potentiel individuel » in Sedeaud A, Colombo C. *Individualisation de l'entraînement*, Paris, INSEP, « Savoirs Sciences », 2022, 17-36.
2. Groperrin M, **Difernand A**, « Regards et retours critiques » in Sedeaud A. *Les données au service du sport de haut niveau : apports, leviers et limites*, Paris, INSEP, « Savoirs Sciences », 2022, 17-36.

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CONFERENCE CONTRIBUTIONS

1. 53èmes Journées de Statistique de la Société Française de Statistique (SFdS), 2022, Lyon, France. **Difernand A**, De Laroche Lambert Q, Pla R, Antero J, Toussaint JF, Sedeaud A. Oral presentation: Relative Age Effect Among French Swimmers.
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3. Rentrée Ecole Doctorale 566, 2022, Paris, France. **Difernand A**, De Laroche Lambert Q, Pla R, Antero J, Toussaint JF, Sedeaud A. Oral presentation: Relative Age Effect Among French Swimmers.
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5. Café de la performance du Stade Rochelais, 2023, La Rochelle, France. **Difernand A**. Oral presentation: Estimation de potentiels – La prise en compte de la maturation, de paramètres physiques, psychosociales dans la détection du jeune joueur de rugby.
6. 28th Annual Congress of the European College of Sport Science (ECSS), 2023, Paris, France. **Difernand A**, Mallet A, De Laroche Lambert Q, Miguens N, Pla R, Antero J, Toussaint JF, Sedeaud A. Poster presentation: Dropout among French swimmers: gender, relative age effect and performance level influences.

Other publications

PEER-REVIEWED PAPERS

1. Schipman J, Sauliere G, Marc A, Hamri I, Le Toquin B, Rivallant Y, **Difernand A**, Toussaint JF, Sedeaud A. The COVID-19 pandemic impact on the best performers in athletics and swimming among paralympic and non-disabled athletes. *Journal of Sports Medicine & Physical Fitness*. 2022 Dec;62(12):1605-1614. doi: 10.23736/S0022-4707.22.13365-7. Epub 2022 Feb 18. PMID: 35179330.
2. Miguens N, Pla R, **Difernand A**, Toussaint JF, Sedeaud A. Postlockdown Performance in French Swimming Championships. *International Journal of Sports Physiology and Performance*. 2022 Jun 10;17(8):1196-1204. doi: 10.1123/ijsp.2021-0514. PMID: 35690394.
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List of Abbreviations

LTAD: Long Term Athlete Development

PHV: Peak of Height Velocity

RAE: Relative Age Effect

YOG: Youth Olympic Games

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GENERAL INTRODUCTION

An introduction to age

'Avoir l'âge de raison', 'être dans la force ou dans la fleur de l'âge', 'Act your age', 'You can't teach an old dog new tricks' etc. Languages are rich in idioms that touch upon this subject, and this is no coincidence. Age has always been a pervasive characteristic in our societies, with significant implications across various domains, including science and technology, human and social sciences, culture and society.

Many ancient civilizations, such as the Egyptians, Greeks, and Romans, had distinct ways of marking age-related milestones. These methods often revolved around cultural rituals and religious ceremonies. In modern times, the advent of more precise record-keeping and the spread of literacy have facilitated the documentation of birthdates. The concept of age as a chronological measure gained increasing importance during this period. In the 21st century, age plays a critical role in various fields like education, employment, healthcare and beyond, notably by a concomitant increase in the lifespan. Technological advancements have enabled increasingly precise age measurement, and discussions on the distinctions between biological age, psychological age, and social age have become more common in certain contexts.

In the realm of sports, performance is highly age-dependent. This relationship between age and performance stands out as a predominant factor in the world of athletics. Numerous methodologies have been developed to elucidate this connection and estimate the age at which peak performance is reached.

Achieving top-level performance

The pinnacle of top-level sports is represented by the Olympic Games, world championships, world cups, continental championships, and national championships—prestigious events that athletes aspire to participate in and excel at. However, the journey towards these premier competitions is quite extensive. Some individuals initiate their path by joining a sports club and obtaining a federation license, while others engage in sports solely within their school environment. There are also those who partake in casual matches with friends or neighbors on a nearby soccer field. As time progresses, the commitment deepens, training frequency intensifies, and thoughts about a potential athletic career begin to appear. Hence, the question

arises: what is the optimal strategy for enhancing the likelihood of attaining top-level athlete status and pursuing the shared dream of an Olympic gold medal?

General objective

It is within this perspective that this thesis proposes to investigate at the beginnings of a sporting career from the detection and selection techniques of the federation's point of view. The importance of exact age will be highlighted in the first two studies. At the age of 10, a single year corresponds to 10% of a child's lifetime. Within this 10%, numerous transformations can occur, yet it still constitutes an age category. There are different types of ages, each with its own significance in the life of a young athlete.: chronological age (which determines their age category), relative age (which establishes the age difference in comparison to others), and biological age (which can lead to substantial functional disparities within the same age category). These factors help provide context for the performance differences among athletes. These differences in performance may in turn be the cause of dropouts, which is the subject of the third study. This aforementioned study looks at the influence of birth quarter, sex and performance level on whether or not athletes drop out of competitive sport. The fourth study focuses on biological age and its impact on performances. Based on the performances of participants in the French Junior Swimming Championships, the focus will be on the maturation of the swimmers and its potential link with performance. Finally, there will also be an exploration of the future of young swimmers by observing their participation in international championships in the fifth study. Thus, the overall objective of this thesis is to understand the influence of chronological and biological age on detection and selection and how it affects future performance and dropout.

STATE OF THE ART

How to consider age in sport?

Traditional approach: calendar age

Definition

Sports categories are established based on age, specifically the count of years between the year of birth and the ongoing season. This age, often referred to as "calendar age," is defined by the National Institute of Statistics and Economic Studies (INSEE) as the gap between the current year and an individual's year of birth. In simpler terms, it signifies the number of years a person has lived, typically expressed as a whole number.

Application

To ensure fairness and equity, individuals are grouped based on their age into specific age categories, with the goal of bringing together individuals with similar abilities. In competitive sport in France, similar to the educational system, young participants are organized into age categories: U12, U14, U16, U18 and junior (U20). The origin of the older age categories dates can be traced back to the 19th century in England when young people started participating in sports at around 15 years old [1]. The primary motivation behind the creation of these age categories was to promote sports competitions among peers of the same age. Subsequently, younger age categories were introduced, with medical approval for children to participate in sports [2]. These age categories typically cover a two-year age span, but they can vary based on the sport and sex [3] [4] [5] (Figure 1).

	SWIMMING		TRACK-AND-FIELD		SKI	
Age	Females	Males	Females	Males	Females	Males
6	<i>Avenirs</i>	<i>Avenirs</i>	<i>Baby Athletics</i>		U8	
7			U9 / <i>Eveil Athlétique</i>			
8					U12 / <i>Poussins</i>	
9			U14 / <i>Benjamins</i>			
10					U16 / <i>Minimes</i>	
11			U18 / <i>Cadets</i>			
12	<i>Benjamines</i>	<i>Benjamins</i>			U20 / <i>Juniors</i>	
13			U23 / <i>Espoirs</i>			
14	<i>Juniores</i>	<i>Juniors</i>			U30	
15			Seniors			
16					Seniors	
17			Seniors			
18	Seniors	Seniors			Seniors	
19			Seniors			
20					Seniors	
21			Seniors			
22					Seniors	
23			Seniors			
24	Seniors					

Table 1: Age categories in different sports from 6 to 24 years old.

The words displayed in italics correspond to the French denominations and do not have a clear equivalent in other national federations.

Limits

The main issue with calendar age categories is that they can lead to inequality among athletes within the same age category. In fact, in a 2-year-old category, there can be up to a 2-year difference between an athlete born just after the cutoff and one born just before the cutoff, and yet both are competing in the same category. This clearly demonstrates the limitations of

this calendar-based approach, necessitating alternative methods that consider additional factors beyond just the year of birth.

Chronological age: accurate calendar age

Definition

Commonly referred as decimal age, chronological age represents the difference between the given date and the individual's date of birth, expressed in years but in decimal form [6]. This means that in addition to the year of birth, the month and day of birth are also considered. This age is very similar to relative age, which indicates how old an individual is within an age group. For example, if you were born on August 19th 2010, your chronological age for the corresponding year would be 13,66.

Relative age

The relative age could be defined as the exact age compared to the current day or relative to the date of the competition. This highlights that two young athletes in the U12 category in athletics can be 10 years and 47 days old for one of them while this opponent can be 11 years and 324 days old. In sport, the concept of 'relative age' was introduced, referred to the difference between a child's date of birth and the cutoff date of the age category in which children of the same age group are placed [7].

Relative age effect

Definition

When considering 2-year age categories, there can be a maximum difference of 730 days between individuals in the same category. However, among elite athletes, especially those selected for the national team or participating in training centers, a distinct pattern emerges. There is a skewed distribution of athletes, with an over-representation of individuals born early

in the year or just after the age category cut-off, and an under-representation of those born later in the year, just before the cut-off. This phenomenon is commonly referred to as the relative age effect (RAE) [8]. RAE has been consistently observed across various sports[9].

Education

Before being observed in the field of sport, the relative age effect was already known in the field of English education. In 1961, Pidgeon and Dodds reported that being born in different months had an impact on the duration spent at nursery school [8]. For instance, children born before June in year X would start school in the summer of year x+5, attend for two years and one quarter, and leave in year x+7 [9]. On the other hand, those born in June or later would start school in the autumn of the year x+5, attend for two years, and leave in year x+7 [9]. Teachers are well aware of this phenomenon [8]. However, limited research has been conducted to explore the potential effects of this difference on future performance. Some have suggested that more time spent at school may be associated with better performance in assessments [8].

Jinks [10] also made a similar assumption when comparing the distribution of birth months between the highest and lowest performing classes of the same age group at the age of 11. Children born during the summer, who started school one quarter later (equivalent to being born just before the age category cutoff), were less likely to be present in the highest-performing classes for both boys and girls. Additionally, Armstrong [11] conducted a study on the performance of a population of children of the same age on national tests. Although no significant differences were found overall, when considering the distinction between school locations (urban or rural areas), it was observed that summer-born children attending small rural schools had a slight advantage over those attending large urban schools.

In France, the education system follows a slightly different approach: children can join nursery school from the age of 3. As the school year begins in September, children born before September will be 3 years old at the start of the academic year and will have the opportunity to attend 3 years of nursery school before moving on to primary school [12]. On the other hand, those born after September are typically expected to wait until the following academic year,

with some exceptions [12]. To my knowledge, no study has demonstrated a relative age effect in French schools.

Team sports

The first studies that highlighted the relative age effect in sport focused on ice hockey in America. Barnsley and Thompson observed an inhomogeneous distribution with an over-representation of players born early in the year among NHL hockey players and two other major leagues in Canada [13], [14]. Only 16.2% of the sample came from the last quarter of birth, while nearly 2 times more (32.0%) were born in the first quarter [14]. This finding suggested a potential relationship between the relative age effect and access to high-level sports. A similar study was also conducted in baseball [15], although the effect appeared to be less significant compared to ice hockey.

Similarly, in the context of field hockey, initial studies on the relative age effect revealed an over-representation of athletes born at the beginning of the year and an under-representation of athletes born towards the end of the year in the elite teams. Helsen et al. [16] observed a linear relationship between birth month and the number of athletes in each birth month, through the use of linear regression. This relationship was particularly evident among young individuals aged 12 to 16. However, no such relationship was found among 6 to 10-year-olds.

Numerous studies conducted in the early 21st century have explored the relative age effect, particularly in soccer [7], [16]–[30], volleyball [31]–[43], basketball [34], [44]–[56], rugby [57]–[69] and handball [34], [47], [48], [58], [70]–[78]. The consistent findings across these studies revealed that the majority of young athletes are born in the first quarter after the cutoff date. However, depending on the country and the sport, the cutoff may vary. Commonly used cutoff dates are January 1st, which aligns with the start of the calendar year, and September 1st, which coincides with the beginning of the new school year. Additionally, in these studies, a less significant relative age effect has been observed during the years surrounding the age of majority or within the age groups between 6 and 10 years old [9]. This could be attributed to limited available data before the age of 10 or smaller sample sizes, making the observed patterns less representative of the overall population. As athletes progress in age, only the most

talented and psychologically resilient individuals tend to remain in the sport, having successfully overcome challenges to fully commit to their sporting career [64], [65].

Soccer, in particular, stands out as an interesting sport when examining the relative age effect. Some theories suggest that the relative age effect is correlated with the sport's popularity [48], [79], and soccer has become one of the most widely practiced sports worldwide in recent decades. Its accessibility, requiring minimal equipment and facilities, allows young children to engage in casual play easily, often seen in street games. Moreover, being a team sport, soccer encourages broad participation. The sport's widespread media coverage, including events like the World Cup, European Cup, Champions League, also contributes to its appeal for children. In fact, soccer is the most widely practiced sport in the world. In France, it is the only sport that boasts more than 2 million licensed players.

In Belgium, a relative age effect was observed in a population of soccer players selected for the 2nd and 3rd national divisions (semi-professional and amateur) [80]. The effect was more pronounced among young players. When considering the number of minutes played, there was a noticeable over-representation of players born in the 1st quarter of their respective age category. Another study focused on European male and female players from U12 to U21 and U12 to U18, respectively, including participants in UEFA tournaments [30]. Once again, the RAE was present in the youngest categories and found to be the least significant in the older categories, such as U18 girls and U21 boys, particularly those who participated in the tournaments. On the contrary, the U15, U16 and U17 categories demonstrated a correlation between birth months and the number of players.

However, the relative age effect is not limited to the team sports previously discussed, as it can also be found in various other sports [8], [9], [26], [37], [44], [48], [81]–[107].

Individual sports

Studies have examined the relative age effect in individual sports, particularly in combat sports like judo, boxing and taekwondo. Judo, being a weight category sport, groups judokas are based on weight from a young age, which may introduce bias towards biological maturity. In research

spanning over 40 years of data, Albuquerque et al. [96] investigated the relative age effect in 2427 judokas who competed in the Olympic Games, taking into consideration both sex and weight category. Their findings indicated no relative age effect in the light to medium weight categories. However, among medal-winning men and male athletes competing in the heavyweight categories, a relative age effect was observed between the two semesters of the year, with a higher proportion of athletes born in the first semester of the year [107]. This can be explained by the fact that the heaviest weight category has no upper bound and includes all the heaviest athletes. Nonetheless, the heaviest athletes often reach their growth peak earlier and are more likely to be selected, in accordance with Cobley's maturation-selection hypothesis which will be developed in an upcoming section. These findings were further explored and confirmed by Fukuda et al. , who analyzed data from cadet, junior and senior Olympic Games and World Championships from 1993 to 2020 [94]. Relative age effect was observed in the heavy and medium weight categories in junior and senior boys, and also in cadet heavy girls. However, no RAE was detected in karate [108] and taekwondo Olympians [96] and French female and male boxers.

A study explored the relative age effect within the three fencing events (epee, sabre and foil) among the top 200 senior and junior athletes from 2007 to 2016 [109]. Among senior athletes, RAE was observed only in female epee and sabre events, as well as in male sabre [109]. In contrast, among juniors, a relative age effect was found in all events and for both sexes, except for female sabre category [109].

In tennis, a relative age effect is also present. Gerdin et al. observed that 64.10% of Swedish male tennis players who reached the top 10 were born in the first half of the year [110]. This trend is confirmed within the top-level of women's tennis, where 62% of top 10 WTA female tennis players between 2007 and 2016 were born in the first half of the year [111]. When focusing on younger players, the results are more pronounced. Indeed, 70.2% of the German national selection for U12-U18 tennis were born in the first half of the year [112].

More in-depth research has been carried out into track-and-field and swimming.

Track-and-field

The initial research on track-and-field focused on competitors at the Cadet and Junior World Championships. These studies revealed an age effect regardless of the competition and sex, with a stronger effect observed in cadets than in juniors, and a more pronounced effect in boys than in girls [103]. These worldwide population studies were conducted on relatively older categories, likely due to data availability. However, a Swiss study examined a younger age group, ranging from 8 and 15 years old, and included more than 7000 boys participating in the 60m sprint. This study investigates the RAE at different levels of performance [99]. It was observed that the higher the performance level, the more evident the presence of RAE in the age category and sex being considered. This observation aligns with the definition of the RAE as a phenomenon frequently found among elite athletes. Therefore, it is not surprising to witness a stronger RAE when analyzing the highest levels of performance.

Brustio et al. investigated the performance of athletes within the international top 100 rankings from 2010 to 2018 across various age categories (U18, U20 and senior level) and athletic events (ranging from 100m to 5000m, including hurdles, jumps and throws) [102]. The findings indicate that individuals born in the first quarter of the year are more likely to be represented in the top 100 rankings compared to those born in the last quarter. This trend was particularly evident in U18 and U20 athletes but does not show a significant effect for seniors, with a stronger relative age effect observed in boys than for girls. This study also revealed that middle-distance events were less affected by RAE compared to throws, where the effects were more pronounced than in other disciplines. The same researchers' team published recently a study based on 5,766 sprinters and 5,863 jumpers [113]. They observed skewed quartile distributions in the Under 18. Moreover, RAE magnitude increased according to performance level (from Top 200 to Top 50) and was higher in males than females [113].

When analyzing the RAE, it is essential to consider the age category range, which can span one year, two years or even more. Brazo-Sayavera et al. [101] investigated the RAE among 642 Spanish athletes in the U18 and U20 age groups. Their findings revealed that, regardless of the category and sex, the RAE had the most significant impact in the youngest year of the age category, commonly referred to as “year 1”. The study focused on elite athletes, including those

selected to participate in international championships. Despite this focus, and after conducting a review of the existing literature on the subject, the authors suggest that the RAE might tend to decrease after reaching the peak of maturation which will be further developed.

According to Kearney et al. [114], the RAE appears to be more significant at younger ages. To investigate, they examined English athletes across different age groups, including U13, U15, U17 and senior levels. They observed that the RAE was pronounced in U13, among both in girls and boys, particularly among those ranked at the highest levels. Both sprints and hurdles showed the highest RAE for both sexes. Confirming previous research findings, they also observed that middle-distance races did not any RAE for girls from U15 to senior level.

Swimming

To date, few studies have investigated the RAE in swimming. Costa et al. [106] conducted an analysis using FINA points to explore the relationship between RAE and performance in individual events in the U12 to U16 categories. Their findings suggested that there was no significant impact on short-term performance indicators.

Another research study examine the impact of the RAE on short-term performance indicators, especially Olympic medalists, among swimmers who participated in the London 2012 Olympic Games [82]. Their finding revealed that the quarter of birth did not show any significant correlation with winning medals.[82]. However, the researchers observed the presence of RAE only among Asian swimmers when analyzing medals by continents.

A Hungarian study investigated RAE within long-term development programs during the selection processes for junior swimmers [115]. The study revealed that individuals born in first quarter of the year (males: 36%; females: 40%) were more likely to be selected than those born in the fourth quarter (males: 9%; females: 14%) [115]. Furthermore, when extending the study to examine those selected for the next stage of the talent development program, most individuals born in quarter 1 was observed.

Several studies [8], [104] have reached a consensus that the impact of RAE on performance decreases as swimmers progress in age, relative to their chronological age. RAE was observed in all categories studied, except for the oldest group, at the age of 14 for female swimmers in the 100m and 200m breaststroke events, and at the age of 15 for male swimmers in the 100m freestyle event. Furthermore, Staub et al. [81] highlighted the absence of RAE in girls aged 17 to 18 in the events of the 50m freestyle, 50m breaststroke, 400m freestyle, 200m individual medley, and 100m butterfly. Conversely, for boys, the impact of RAE tended to decrease from the age of 17.

Consequences

The relative age effect can lead to various consequences, with one of them being the maturation-selection hypothesis.

Maturation-selection hypothesis

Historically, the maturational hypothesis indicates the fact that children born in the summer months consistently fall within the youngest range of an annual age group [116], [117]. Furthermore, assuming comparable growth rates and the beginning of puberty, the least mature individuals within a cohort will exhibit noticeable physical and cognitive variations over the course of a single 12-month period [116], [117]. The Cobley's maturation-selection hypothesis is a theory that posits that due to differences in biological maturity among young athletes within the same age cohort, more mature athletes are more likely to be selected and succeed in sports, potentially creating a competitive imbalance [9], [118]. This hypothesis suggests that more mature athletes, who have an advantage in their physical development, may outperform in terms of sports performance less mature and younger athletes in the same age category [9], [118]. This theory was developed in response to the observation that athletes born earlier in the year (and thus more mature for their age) seemed to be overrepresented in youth teams and performance sports [9], [118]. This hypothesis highlights indirectly how differences in the timing of biological maturity can influence athlete selection and have an impact on their long-term sports development [9], [118]. These advantages could originate from increased experience resulting from extended practice and skill development, as well as from

the progression of morphological, neurological, motor, and psychosocial maturation [30], [119], [120]. Consequently, athletes with a relatively older age within their cohort tend to outperform their peers. This success then amplifies their likelihood of being chosen for continental or international competitions, or specialized training programs. On the other hand, younger players might experience reduced attention, support, and coaching expertise owing to their comparatively lower level of performance. [9]. As a result, this can lead to further negative consequences such as demotivation or dropout.

Demotivation and dropout

When young athletes receive less attention in their learning process, they may suffer a drop-in motivation. Yet a number of studies show that motivation is essential if people are to flourish in their sporting activities and perform well [121], [122]. Several situations can drive a young athlete to drop out of a particular sport or the practice of sport in general. This study highlights several reasons that lead to withdrawal among Finnish athletes [123] or Canadian swimmers [124]: loss of interest, boredom in the current activity, interest in another activity, conflict with the coach, loss of pleasure, frequency of injuries, stagnation of performance or skills. In contrast, athletes who persist in the same sport usually enjoy greater parental support, and the rewards they obtain from their success in competitions create a virtuous circle in favor of commitment [124], though too much pressure from parents during adolescence may also lead to disengagement [125].

Loss of potentials or not?

One possibility to assess the loss of potential great athletes is to measure the conversion rate (from younger categories to senior) and the insertion rate (from senior to younger categories). However, only 10 to 30% of very high-level senior athletes were already in the youth categories [126]. Indeed, in their study, Güllish et al. reviewed 189 articles, totaling 61,344 athletes [126]. The studies were categorized into two types based on the type of athletes: 110 studies comprising 38,383 junior athletes and 79 studies with 22,961 senior athletes [126]. The objective of this review was to examine the junior-to-senior conversion rate among 34 sports (track and fields, swimming, cycling, tennis, basketball, handball, rugby, soccer, rowing,

triathlon, power lifting, badminton, baseball, curling, field hockey, tennis table, water-polo, boxing, wrestling, gymnastics, skate, diving, horsing, pentathlon, sailing, archery, shooting, ski, taekwondo, judo, ice hockey, volleyball, or canoe kayak. The main question of the study was how many junior athletes reached a similar level as seniors, and conversely, how many senior athletes came from an equivalent level when they were in the junior category [126]. Additionally, the study looked at cases where athletes achieved an elite level both as juniors and seniors. The findings revealed that nearly 9 out of 10 international-level junior athletes (U18) did not reach the international senior level [126]. Likewise, approximately 82% of senior international athletes did not have prior international junior experience [126]. Only 7% of the athletes achieved international-level performance in both the junior and senior categories, highlighting significant differences between these two populations [126]. Interpretations of these results may be that a considerable number of young athletes drop out and early success does not necessarily preclude senior success. This extremely low conversion rate was observed in different sports. For example, when specifically focusing on the Italian women's national football team, Brustio et al. found that only 17% of the players out of the initial 198 U17 players eventually made it to the senior national team (**Figure 1**) [127].

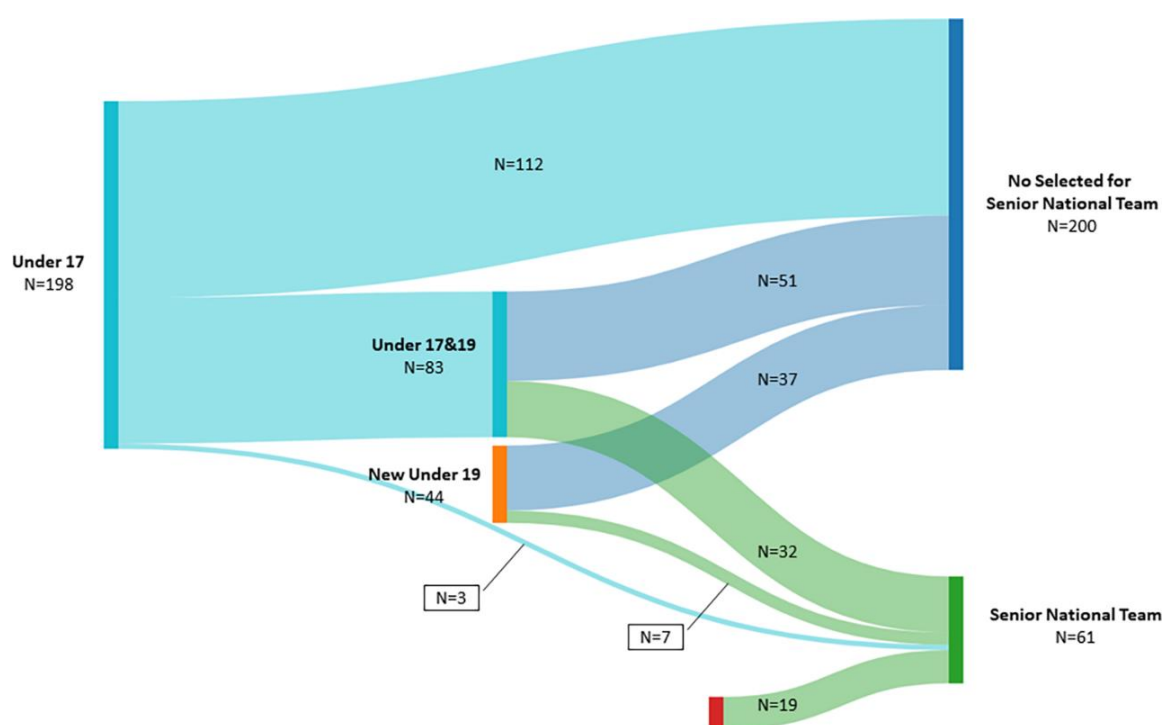


Figure 1: Youth-to-senior transition rate.

Overall visual inspection of the youth-to-senior transition rate. The Sankey diagram provides the number of players able to reach the National Senior team from Under 17, 19 (or both together). The figure also provides the number of players that were not selected for Senior National Team. (From Brustio et al., 2023 [127])

The observation is quite similar for boys, where the conversion rate hovers around 10-20% of U16-U19 players who are subsequently selected for the senior national team, regardless of their positions [128]. However, Brustio et al.'s study identifies a difference in transition rates between 10 and 26% for male swimmers and between 23 and 33% for female swimmers based on their age [129].

Barreiros et al., on the other hand, investigate the "pre-juniors," those under 16 years old, in the following sports: volleyball, swimming, and judo [130]. They note that, among girls, while 46 to 57% of pre-juniors are newly selected for the juniors, less than one-third of pre-juniors are called up to the senior national team [130]. For boys, the turnover is less significant, with 55% of pre-juniors being called up to the senior national team in volleyball, but only 28% in judo [130]. Interestingly, Li et al.'s study on combat sports shows that 61% of junior medalists and 90% of junior combatants in seniors achieve at least one international medal in seniors [131]. That is what we called this phenomenon the "earlier success paradox". This paradox relies on the fact that from one side being successful in the young category does not prevail over future success, and the other side the best young people (medalists) considerably increase their rate of conversion from the junior to senior elite level [132]. In accordance with this paradox, Boccia et al [133] observe the performance trajectories of the top long jumpers and high jumpers over a decade, they find that 60% of 16-year-old athletes did not maintain the same level of performance in seniors. According to the authors, success at a young age is not a strong indicator of success in seniors; rather, the athlete's performance progression is far more decisive [133].

Another example is observed in a sample of 8,000 cyclists over 24 years. It was discovered that 29% of elite senior cyclists had participated in junior World Championships, and 34% of Junior World Championships cyclists had participated in major elite senior competitions [134]. However, this study mainly focuses on participation rather than success [134]. In contrast,

tennis could appear as a perfect counterexample looking at only one study. Taking the top 10 players between 2007 and 2017, totaling 82 players (44% women), 95% of the top female players and 92% of the top male players had won at least one title in singles or doubles in junior categories [135]. However, if you look at the study of Brouwers et al., who have not only applied the top down approach (insertion rate) but also the bottom up method (conversion rate), we can observe that only 1.3% of players in the top 20 ATP and 1.1% of players in the top 20 WTA have performed on the youth circuit [136]. Nonetheless, winners, runners-up and semifinalist in youth tournament significantly increase their conversion rate with 18.2%, 9.5% and 4.8% respectively [136]. These two studies illustrate, in one specific sport, the “earlier success paradox”.

Despite these important dropouts and lost sight, it happens that some athletes endure over time. One possible explanation is that these underestimated young athletes, who may not have been noticed in the younger age categories, can develop a strong desire to prove their worth once they reach a higher level of physical maturity and technical competences. Their late growth can give them an unexpected advantage in terms of strength, size, coordination, and other physical factors relevant to their sport [64], [65], [137].

Potential compensatory mechanisms

Potential explanatory mechanisms have been put forward, evoking psychological aspects, identity construction in the face of challenges, learning capacities or resilience [64], [65], [137]. In team sports once again, some are able to achieve and maintain, even increase their competitiveness and reduce the limiting impacts of the relative age effect during their development processes [138], [139]. The confrontation and the nature of challenges and experiences that are more difficult to overcome for the youngest during the development phases would generate adaptation and resilience capacities that are useful later for the very high level [140], [141]. Many theories supporting these various forms of “mental toughness” emphasize the importance of overcoming adversity and developing an ability to cope [142], [143]. Indeed, experiencing some adversity can have beneficial effects on human growth and development [137]. A study of semi-structured interviews with 10 Olympic champions in 8 different sports revealed common characteristics. Experiences related to adversity have been

deemed essential to the psychological development and performance of these Olympic champions [137]. These results echo other studies conducted on Olympians. The ability to positively adapt to adversity as critically important determinants of optimal athletic performance [144], [145]. Some authors have suggested that coping with difficulties in life may contribute to a greater later propensity for positive coping. Mechanisms, such as creating a sense of mastery over past adversity, fostered by perceived control and a belief in managing successfully, as well as establishing effective social support networks appear to be important [146], [147]. Exposure to stressors was a key feature of the stress-resilience-performance relationship of Olympic champions [144]. Most of the participants argued that if they had not experienced certain types of stressors at specific times, including extremely difficult events, they would not have won their gold medals [144]. Among these events are repeated non-selection, significant sporting failures, serious injuries or even the death of loved ones. Faced with these capacities for resilience and adaptation, different names have been formulated such as post-traumatic growth [148], positive adaptation [149] or contradictory growth [150]. The most common athletic adversity identified among Olympic champions was repeated non-selection. Olympic gold medalists have recalled how not being selected for international competitions first leads to an intense feeling of frustration, before leading to increased effort and desire. A real sporting failure, such as disappointment in a major championship, an underperformance at previous Olympic Games or an early defeat during an Olympiad seem to be common and constitutive elements of these 10 Olympic champions [137]. The resulting adversity and trauma fueled the Olympic champions' desire to excel at the highest level. Some authors go further into the benefits of this underdog effect. Younger athletes, able to survive in a system advantageous to their relatively older counterparts, would develop superior technical skills [151], with even reverse effects, where subsequently the younger members of the workforce would injure themselves less [152], and would be better paid [153].

RAE proposed solutions

Beyond these "natural" compensatory effects mentioned in the previous chapter, scientific literature suggests various solutions to address this issue. One of these solutions involves improving communication and knowledge transfer towards athletes, especially among younger ones who are affected by the RAE [154]. Coaches may be aware of the relative age effect in the

field, even without formally measuring it through birth semesters or quarters distribution. While it is crucial for coaches and staff to understand what the RAE is, its effectiveness has not been conclusively demonstrated [20], [29], [155].

On the field

Practical solutions in the field have also been explored, including adjusting the cutoff date each year over a 4-year cycle, differentiating cutoffs based on specific sports [156] or modifying the cutoff range [157]. Although the differences between young athletes may be less over a 9-month period, in team sports, team compositions change, and the cohesion among players may not be sustained. Additionally, suggestions have been made to introduce quotas [14] or regulate the average age of the team [16], [119]. However, implementing these measures on the field can be challenging. One study involved wearing T-shirts with the number of the month of birth to indicate the relative age of the scouts in real time [155]. This approach helped reduce the RAE among the players. Nevertheless, this method was only tested once during a selection process.

This is comparable to the concept of bio-banding, which is defined as grouping juveniles not solely based on their year of birth but according to their physical growth or maturity stage [158]. Within the same year of birth, some individuals may experience different timing and tempo of maturation [159]. By adopting bio-banding, individuals with similar morphology can participate more freely without the fear of competing against stronger or more experienced players, thus allowing them to maximize their potential and enjoyment in sports [158].

Theoretical

A more theoretical approach involves recalibrating performance times in track-and-field [99] or swimming [8] based on exact age and the RAE within the same age group. The objective is to provide relatively younger athletes within the same age category with a more balanced and equitable performance compared to older athletes. However, it should be noted that this method is currently applicable only to individual metric sports, as the performance

recalibration relies on mathematical equations. As a result, it is not yet feasible to apply this approach to match scores or team sports.

Biological age

Definition

The term “biological” is associated with the field of biology [160], originating from the Greek words’ “bios”, which means life and “logos”, referring to science. It encompasses all scientific domains focused on studying living species and the principles of life. Biological age, also known as physiological age or skeletal age, accurately reflects an individual’s specific physiological or functional state.

Development, growth and maturation

The development of young athletes involves two critical processes: growth and biological maturation. Growth is defined by the gradual expansion of certain or all body parts [161]. As age advances, both height and weight increase, along with the expansion of organs [161]. On the other hand, biological maturation signifies the progression towards maturity [161]. It is quantitatively defined, indicating the function of an organ or biological system reaching its fully developed functional state [162]. These phenomena are defined by two terms: tempo and timing. The growth tempo and timing among adolescents vary. “Timing” refers to the moment when a maturational evolution occurs, while “tempo” denotes the pace or duration at which growth takes place, especially the speed of progression for changes [163]. Understanding these concepts is essential when assessing the maturation of young athletes as they contribute to morphological disparities among individuals of the same age.

Several assessment methods are available to determine an adolescent's stage of maturation. These methods include Tanner's method, which assesses sexual maturity based on five classifications of secondary sexual characteristics [164]. Another technique involves using X-

rays to estimate bone maturity as well as longitudinal monitoring of weight and statural growth to calculate somatic maturity [165].

Tanner

Tanner's method revolves around observing the development of pubic hair in both sexes [164]. For boys, it focuses on genital development, while for girls, it assesses breast development as an indicator [164]. The transition from preadolescence to adulthood is characterized by changes in the volume and size of the genitals in boys, and shifts in the shape and volume of the breast areola in girls [164]. The peak of height velocity (PHV), representing the phase of the fastest height growth, is approximately 10 cm per year for boys and slightly less for girls [164]. However, this peak does not occur simultaneously for girls and boys [164]. In girls, it typically occurs between the ages of 11 and 14, whereas in boys, it is observed around two years later [166].

Atlas system and bone-specific scoring

This approach involves using X-ray images of the wrist and hand region of the skeleton, to evaluate the bone age of children by analyzing developmental markers in specific bones within this area [167], [168]. Despite the advantages of each method, a notable drawback exists: exposure to X-rays. If radiation exceeds certain thresholds and accumulates, it can disrupt the functioning of tissues and organs, which is not safe for human bodies.

Theoretical estimation

In the early 2000s, Mirwald et al. introduced a method to estimate the age at peak height velocity (PHV) that was less invasive and more cost-effective [165]. They collected data from three different studies involving over 300 boys and girls aged between 5 and 13 [165]. These participants were measured every six months for variables such as chronological age, weight, sitting height, and standing height [165]. The variable of interest, reflecting the level of physical maturity, was also recorded [165]. The dataset was divided into two sections, one for test and

the other for validation [165]. By considering the interactions among the variables and the ratios between them, approximation equations were established to best fit the maturation data with the explanatory variables [165]. The resulting equations are as follow:

Maturity offset (years)_{girls}

$$= -9.376 + (0.0001882 * (leg\ length * sitting\ height)) \\ + (0.0022 * (age * leg\ length)) + (0.005841 * (age * sitting\ height)) \\ - (0.002658 * (age * mass)) + (0.07693 * (mass\ by\ stature\ ratio * 100))$$

Maturity offset (years)_{boys}

$$= -9.236 + ((0.0002708 * (leg\ length * sitting\ height)) \\ + (-0.001663 * (age * leg\ length)) + (0.007216 * (age * sitting)) + (0.02292 \\ * (mass\ by\ stature\ ratio * 100))$$

However, Moore et al [169] contradict these equations, even though they have been cited and used hundreds of times. By taking two groups of examples of female and then male athletes, they demonstrate that the results are not consistent and the PHV ages are unreliable and true for the early and late mature groups.

His main criticism concerns overfitting. As can be seen, the interactions between the original “inputs” to form the variables in the estimation equation may seem surprising. This is why Moore et al. [169] decided to repeat the study with a larger and more recent population. They kept only the simple interactions between variables (i.e. one variable with another). Once they had obtained the equation, they worked on the model to minimize errors and obtain the most accurate results possible. They then obtain:

$$Maturity\ offset_{girls}(years) = -7.7091333 + (0.0042232 * (age * stature))$$

$$Maturity\ offset_{boys}(years) = -7.999994 + (0.0036124 * (age * stature))$$

Limits

Despite attempts to improve existing estimation equations [170] and research articles that discuss the various possibilities in an attempt to show the best choice [171], there are still a number of criticisms of these estimation equations. Although the population of origin is specified as Canadian or Caucasian, it is a population with a specific phenotype, not necessarily

similar to other origins on other continents. The database used is not made up of sportsmen and women, but the equations obtained from this database are applied to sportsmen and women in order to determine their biological age and make the link with performance, for example. In addition, there is enormous variability in morphological criteria within sports. Between a basketball player and a gymnast, the sports have different demands and morphological requirements [172]. Both will not necessarily reach their PHV age in the same way and at the same time (cf tempo and timing), yet the same equation is used. Despite attempts to improve existing estimation equations [170] and research articles that discuss the various possibilities in an attempt to show the best choice [171], there are still a number of criticisms of these estimation equations. Although the population of origin is specified as Canadian or Caucasian, it is a population with a specific phenotype, not necessarily similar to other origins on other continents. On the one hand, the origin, but on the other, the type of population. This database is not made up of sportsmen and women, but the equations obtained from this database are applied to sportsmen and women in order to determine their biological age and make the link with performance, for example.

However, even if this equation has many limitations that have just been mentioned, from simple criteria such as sitting and standing height and mass, an estimate of the PHV can be provided. This non-binding and non-invasive nature makes it possible to have maturity offset estimation for large populations of young athletes during detection test or all along a detection and development program. It seems more relevant to monitor the evolution of height and mass several times a year, like the evolution of performance according to age. Nevertheless, this type of measurement can be time-consuming and complicated to implement on a large cohort, but provides an individual vision of the evolution and attainment of the PHV.

Age-performance relationship

Moore was a pioneer in 1975 when he initially crafted models to represent the connections between age and performance [173]. These relationships can be captured through the amalgamation of two exponential laws: one ascending (indicating a phase of performance advancement) and the other descending (representing a regression phase) [173]. At the point where these two functions intersect, there emerges an optimal performance zone that aligns

with the zenith of performance, commonly recognized as the performance peak as demonstrated by the examples in the men's 100m, 400m, and 800m races in **Figure 2**.

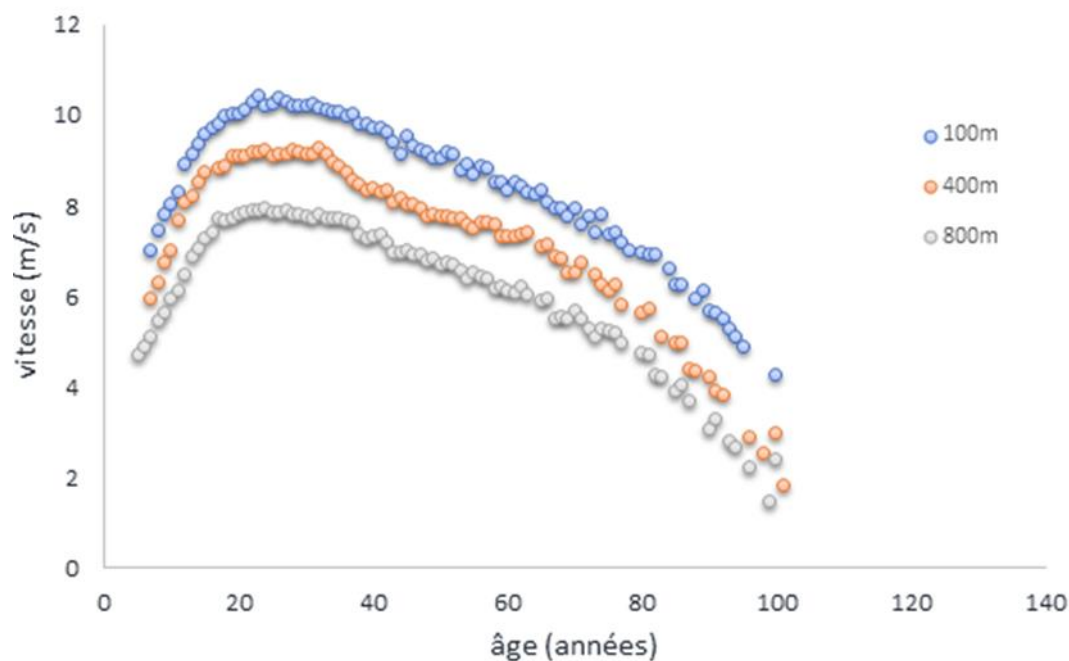


Figure 2: Relationship between age and world's best performance in track-and-field (males 100m in blue curve, males 400m in orange, and males 800m in gray).

This relationship characterizes the ability of numerous physical and physiological parameters inherent to the sport performance in function of the time, such as strength [174], maximal oxygen consumption and respiratory volume [175], volume of pulmonary capillaries [176] or cognitive performance [177]. Whether it corresponds to a physiological component related to the strength performance or to a component related to a quality of endurance, those two variables change over a lifetime or a career and know the impacts of the time.

The declination of age at peak performance for several events such as athletics [178]–[180], running [178], [181], [182], swimming [183], [184], ultra-triathlon [185], [186] or even sports with more difficult-to-measure performance indicators such as tennis, baseball or golf [178], [187] highlight these common trajectories: progression-climax-decline. This relationship, intuitive in what it reveals about our abilities over time, is even found in marathon running (**Figure 3**).

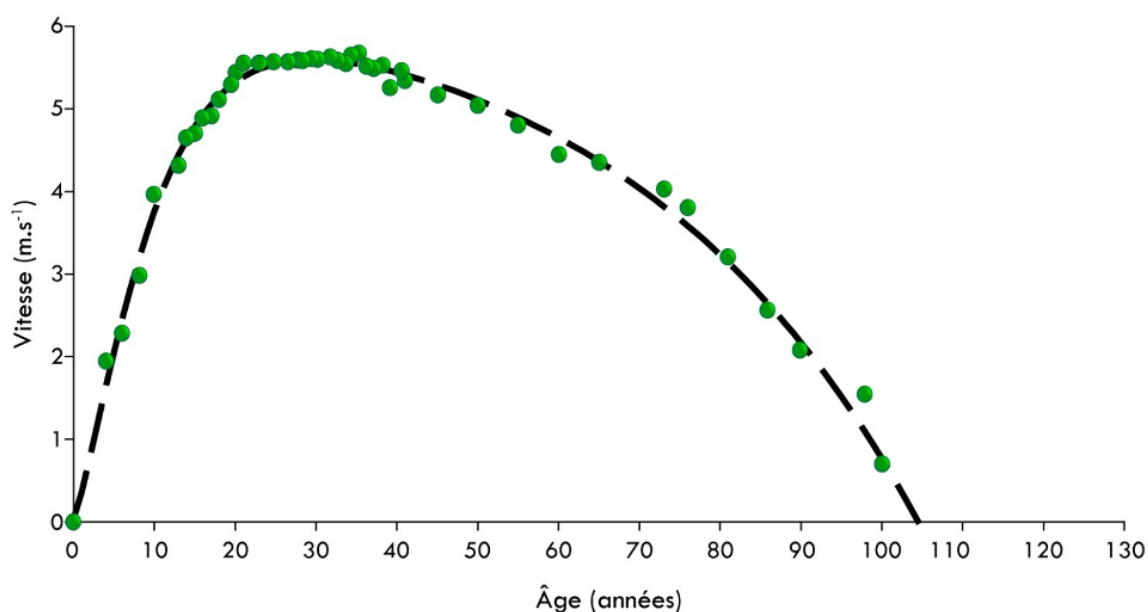


Figure 3: Best male performance as a function of age in marathon.

The dotted line corresponds to the Moore law fitted for this event.

Considering the age at the moment of performance is significant. However, giving equal or even greater importance is the age at which the practice was initiated. This topic is a subject of considerable controversy, with proponents of early specialization on one side and advocates of diversification on the other, each advocating for their preferred approach.

Early specialization

Definition

Early specialization is defined as:

- an intensive training,
- that takes place throughout the year or at least 8 months a year,
- in a unique sport to the exclusion of other activities (sportive or not)
- in prepubescent children [188].

By “early”, authors mean « before the adolescence », more precisely before 12 years old according to the American Orthopaedic Society for Sports Medicine [189]. However, the main concern of early specialization is about health.

Benefits of early specialization

Supporters of early specialization believe that the earlier a child specializes, the more time they will have to work on their technique, tactics, endurance, and cohesion with other team members if it is a team sport. Specifically, it is believed that it takes 10,000 hours to become an expert in the musical domain [190]. Within these 10,000 hours, three components are involved: starting very early, specializing, and increasing the frequency of training and focusing solely on that activity [190]. However, this study can be criticized regarding the studied population. Ericsson et al. observed "elite" musicians and focused on their past practice [190]. Thus, this is an example of survivorship bias (top down approach). Similar observations could be made among the greatest athletes, such as the Williams sisters, Tiger Woods, Michael Jordan, Teddy Riner, Muhammad Ali, and others. It is worth noting that this study pertains to the musical domain, and there may be differences when trying to apply it to the world of sports [190]. The muscular, technical-tactical, and cognitive demands are different. This is the point where those in favor of diversification challenge the notion.

Limits

From a physical point of view, early specialization appears to be a risk factor for injury. Engaging in more physical activity encourages the growth of the musculoskeletal system, while regular exposure to repetitive stress can trigger favorable adaptive responses in the musculoskeletal structures. Nevertheless, too much stress or too many muscular demands on the same part of the body can lead to injury. Indeed, highly skilled athletes are at higher risk for serious overuse injuries [191], [192]. Pasulka et al. also showed, through a clinical study of 1190 athletes, that athletes specialized in a single sport had a significantly higher injury rate than those who were not specialized, possibly due to overtraining [193]. This population of specialized athletes represented only a quarter of the total, in the sports of tennis, gymnastics and dance [193]. A

distinction was made between team and individual athletes. It turned out that individual sports athletes reported a higher level of training and a higher rate of injury [193].

From a nutritional point of view, if a young athlete burns too many calories and does not take enough of the various nutrients needed for their metabolism to work optimally, this can lead to deficiencies (iron, calcium, etc.) and can compromise their growth [194]. Moreover, early specialization has been shown to cause eating disorders [195], [196] a nutritional point of view, if a young athlete burns too many calories and does not take enough of the various nutrients needed for their metabolism to work optimally, this can lead to deficiencies (iron, calcium, etc.) and can compromise their growth [194].

In terms of sexual maturation, when girls do not have a sufficient, healthy and balanced diet, if they are exposed to too much stress and overtraining, it is possible that the age of arrival of their first menstrual periods may be delayed [194]. On the other hand, when menarche has already occurred, these may additionally be the causes of amenorrhea or cycle disorders.

Moreover, early specialization not only exposes athletes to risks of physical and psychological damage but also social [197], [198]. However, as psychological consequences are less visible can also damage the young athlete, there is a risk of burnout and anxiety [194]. Sometimes, parents or other family members put too much pressure on the young athlete [194]. Indeed, by transferring their personal expectations onto their child's life, the latter has an additional source of stress when it comes to succeeding in his sporting career.

In recent review, Mosher et al. [198] identify the risks associated with early specialization but also the possible underlying mechanisms (**Figure 4**).

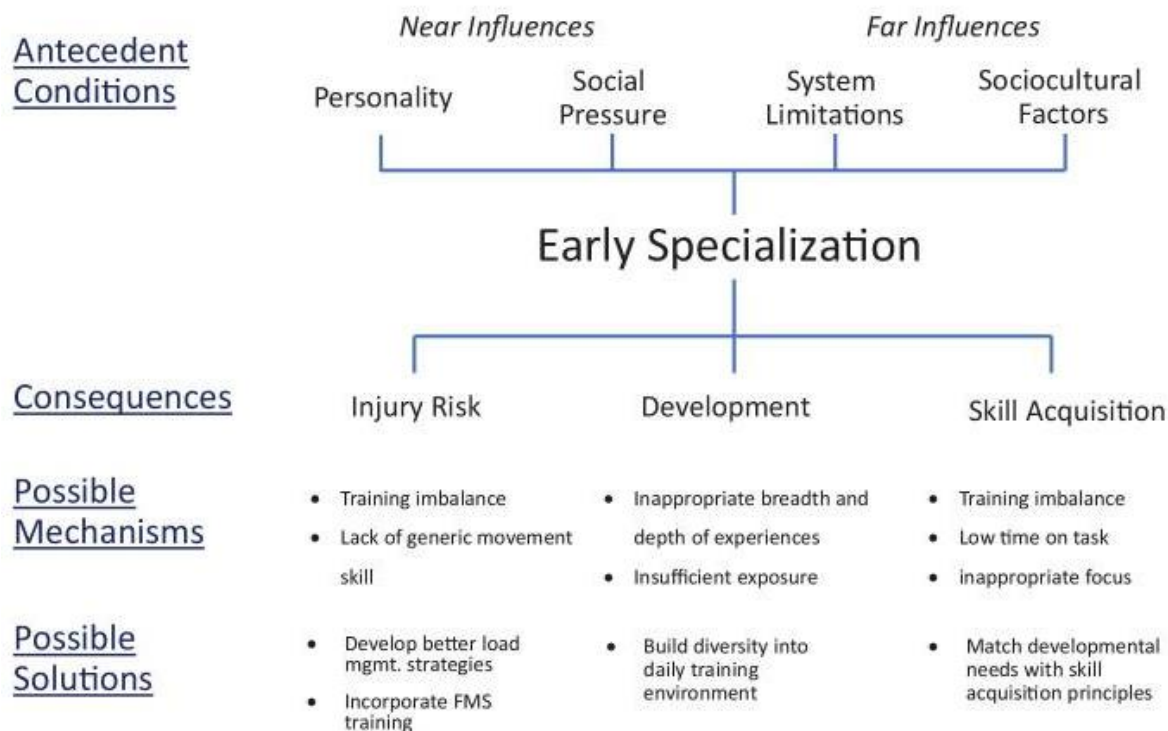


Figure 4: A framework for exploring early specialization in sport.

Fundamental movement skills (FMS) are the basic building blocks of advanced movement that occurs later in athlete development. (From Mosher et al., 2022 [198])

The authors go further by proposing a specialization risk management program based on five pillars:

- establish an “appropriate” environment,
- monitor and evaluate athletes,
- implement integrative neuromuscular programs
- provide psychological skills training
- manage training practices in order to obtain an equilibrium with life.

Diversification

In contrast to early specialization, the concept of diversification or “early sampling” emerges. This approach in sports refers to the practice of exposing young athletes to a variety of sports and physical activities during their development, rather than directing them towards early specialization in a single sport [188], [199], [200]. Côté et al. assume three types of pathways

when an individual starts practicing sports [200] (Figure 5). The first two pathways begin with diversification and lead either to high-level sports through late specialization or to recreational sports [200]. In contrast, the third pathway involves early specialization aimed at achieving high-level success [200].

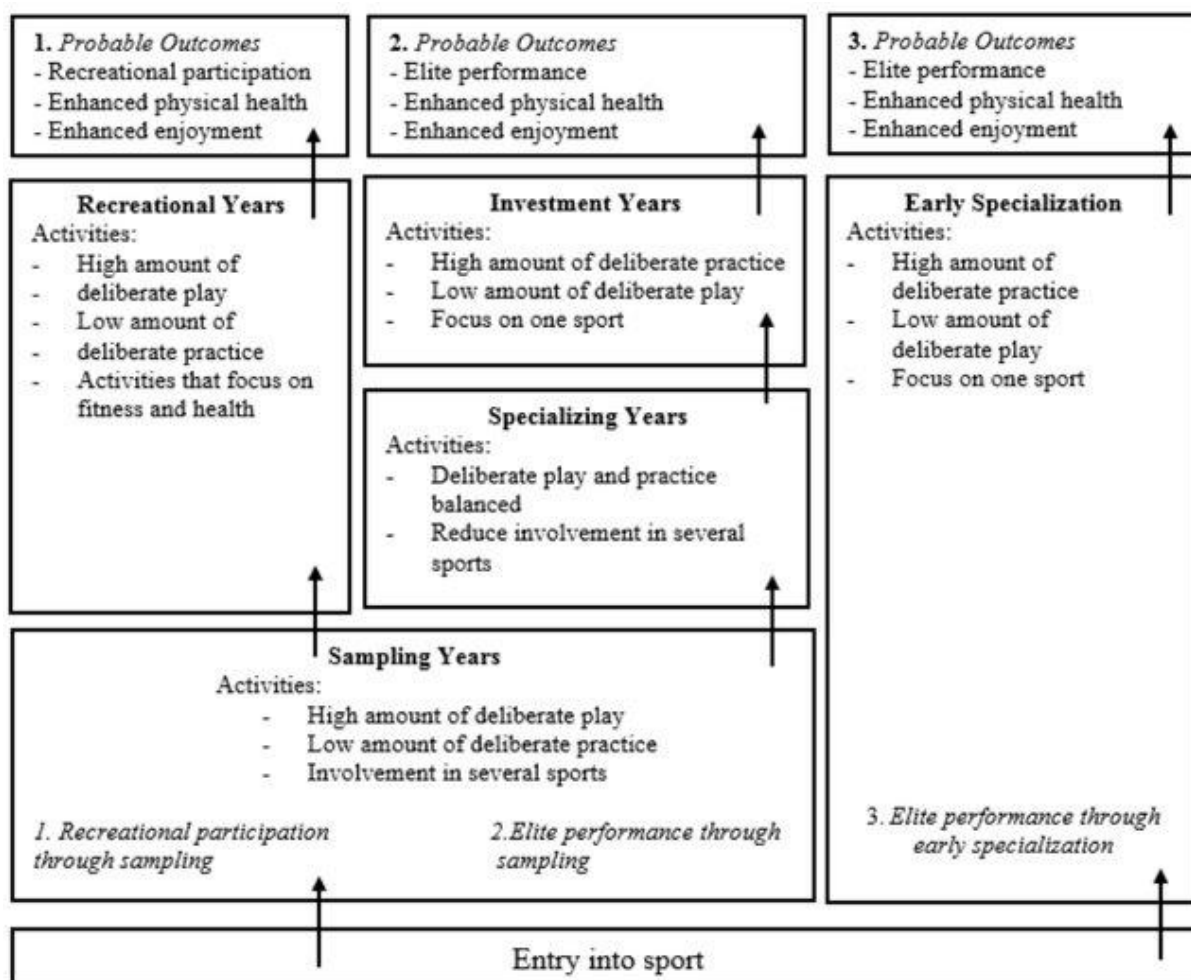


Figure 5: Developmental Model of Sport Participation.

Adapted from Côté et al. (2007). (From Buning et al., 2015 [201])

The "early sampling" approach in sports is based on seven key postulates that influence the athletic development of young athletes [200]. Firstly, this approach does not restrict elite sports participation in disciplines where peak performance is achieved after maturation [200]. Studies indicate that before reaching elite levels in certain sports (such as team sports [202], rowing, triathlon [203], or tennis [204]), young athletes have engaged in other sports. However, this isn't the case in early maturing sports like artistic sports [200], [205]. Secondly, athletes who

engage in deliberate play and diversification during their formative years tend to enjoy longer sporting careers [200], [203]. Thirdly, this approach enables participation in various contexts that promote positive youth development. It encourages diverse developmental experiences and positive relationships with others [200], [206]. Fourthly and fifthly, prioritizing pleasure during deliberate play positively impacts not only an athlete's motivational capital [207] but also their motor and cognitive development [200]. Sixthly, the transition to adolescence empowers young athletes to choose between specializing in a sport or continuing recreational sports participation [200], [208]. Finally, after several years of specialization, adolescents are sufficiently well-rounded and physically, mentally, socially, emotionally, and motorically developed to fully specialize in their chosen sport to attain elite levels [200], [209]. Nonetheless, it is essential to note that the application of these postulates can vary based on individual, cultural, and sporting contexts [200].

With a goal to setting up a healthy sporting environment for young people and reducing the effects of early specialization, a new type of program is being developed: the Long Term Athlete Development (LTAD) [210].

Long Term Athlete Development

Definition

The Long-Term Athlete Development (LTAD) model, conceptualized by Balyi et al., presents itself as a holistic and evolving approach to guide athletes' growth and maturation through different stages of their sports journey. Observing the shortcomings of traditional adult training and competition structures applied to youths aged 6 to 16, Balyi developed LTAD by drawing upon physiological, periodization, and motor learning studies to underscore the need for age and development-specific differentiation [211]. This framework proposes a series of developmental stages, ranging from active participation to specialization, with an emphasis on acquiring fundamental motor skills before focusing on sport-specific skills. The principles of LTAD aim to optimize long-term athletic potential while minimizing risks of overtraining and injuries, judiciously balancing training and recovery for holistic development [212].

Instead, it emphasizes a holistic and long-term perspective, aligning with the understanding that sustained success emerges from gradual and balanced progress. The LTAD model prioritizes five key principles:

- Physical Literacy: The LTAD model advocates for the acquisition of fundamental movement skills in the early stages, ensuring athletes possess a diverse range of basic athletic abilities that can be applied to various sports and activities.
- Developmental Appropriateness: Each phase of LTAD is meticulously tailored to the physical and psychological characteristics of athletes at specific age ranges, ensuring that training methods are developmentally appropriate and avoid undue stress.
- Progressive Overload: The model introduces gradually increasing training loads, skill complexity, and competition intensity over time, promoting consistent and sustainable development while minimizing the risk of overtraining.
- Periodization and Planning: LTAD incorporates the principles of periodization, allowing for the systematic manipulation of training variables to maximize adaptation while preventing stagnation and potential burnout.
- Optimal Recovery and Regeneration: The model recognizes the critical role of recovery in athlete development, advocating for well-structured rest and regeneration strategies to support physical and mental renewal.

The LTAD model encompasses six distinct phases, each catering to specific age groups and developmental markers. These phases facilitate a smooth transition from foundational skill acquisition to elite performance preparation:

- Active Start (Ages 0-6): Encourages unstructured play and fundamental movement skill development through enjoyable and varied physical activities.
- FUNdamentals (Ages 6-9): Refines fundamental motor skills and introduces a range of sports, cultivating a broad base of athletic ability.
- Learn to Train (Ages 9-12): Emphasizes sport-specific skill development alongside a continued focus on fundamental movement skills.
- Train to Train (Ages 12-16): Promotes cross-training and the exploration of various sports, fostering a versatile athlete and reducing early specialization.
- Train to Compete (Ages 16-18): Concentrates on competition readiness, advanced skill refinement, and mental preparation for higher-level performance.

- Train to Win (Ages 18+): Focuses on optimizing performance for elite athletes, incorporating meticulous periodization, recovery, and high-performance training strategies.

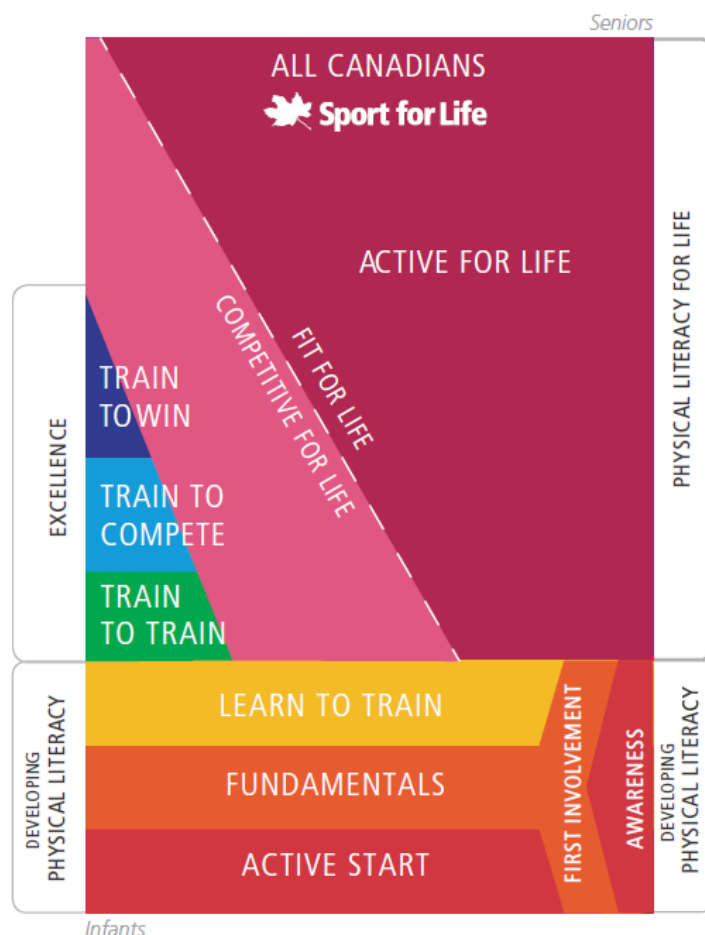


Figure 6: The progression of the Long-Term Athlete Development.

(From Canadian Sport for Life [213])

Examples

The United Kingdom has embraced LTAD principles through UK Sport's "Athlete Performance Pathway" focusing on developing athletes from grassroots to elite levels. The UK's emphasis on structured progression and individualized development plans aligns with LTAD's principles. UK Sport collaborates with national governing bodies to ensure a consistent and progressive athlete development pathway [214] (**Figure 7**). This approach aims to optimize athlete potential while ensuring long-term athlete well-being.

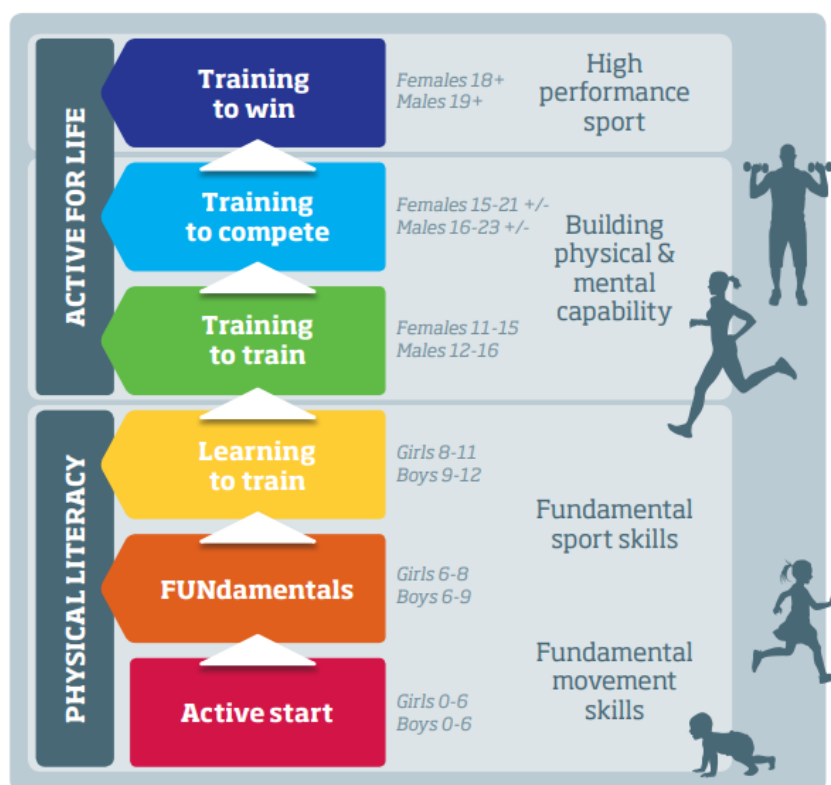


Figure 7: Long-Term Athlete Development in United Kingdom, ages and phases.

(From Sportscotland [214])

In the United States, while the LTAD model has not been universally adopted, its principles have influenced various youth sports organizations. Organizations like USA Hockey [215] or USA Cycling [216] (**Figure 8**) have integrated LTAD concepts into their development pathways, emphasizing skill acquisition, age-appropriate training, and late specialization [215]. While LTAD implementation may vary, its principles guide efforts to enhance athlete development across diverse sports in the United States.



Figure 8: American Development Model (ADM) in Cycling.

Infographics (From USA Cycling, [216])

Limits

The LTAD model, while recognized for its comprehensive and systematic approach to athlete progression, is not without its limitations. One prominent challenge lies in the diverse cultural and sporting contexts across different countries, which can hinder the universal application of LTAD principles [6]. The unique sporting needs, cultural practices, and societal values of each region may necessitate adaptations that deviate from the standardized LTAD phases [6]. Adaptations are required not only on a national level but also at the individual level. Young athletes do not all progress at the same rate in terms of maturation, growth, abilities, and other factors. As a result, they may not perfectly align with the age ranges specified in the program [217]. Furthermore, the LTAD model's emphasis on late specialization may be at odds with the demands of certain sports that require early skill acquisition and specialization for optimal performance. While LTAD promotes a well-rounded skill set, some disciplines may necessitate targeted training at an earlier age, raising questions about the model's adaptability to these specific requirements [199]. The ever-evolving nature of sports presents another challenge. Sport trends, regulations, and competition formats constantly evolve, necessitating a model like LTAD to remain agile and adaptable. Striking a balance between the stability of a structured framework and the need to accommodate emerging developments within the sports landscape

is a delicate endeavor [218]. Lastly, the psychological well-being of young athletes may be impacted by the long-term focus of the LTAD model. The pursuit of sustained athletic excellence can inadvertently lead to heightened expectations, stress, and psychological pressure among young athletes. Balancing the drive for long-term success with the athletes' overall well-being is a multifaceted consideration that warrants attention [219].

RESEARCH QUESTIONS

The collection of studies mentioned in the literature review has allowed the identification of initial guidelines concerning the detection and selection of young athletes. One hand, detection focuses on discovering future performers who are not yet engaged in the specific sport in question. On the other hand, selection aims to chosen athletes to be part of a specific team or program based on their performance and abilities. However, one of the first surprising observations that leads to conducting this thesis arises from the very low French conversion rate between junior and senior categories. Indeed, between the Youth Olympic Games medalists and the Olympic Games, only one out of six French athletes replicated the performance of winning gold and becoming an Olympic champion, resulting in a conversion rate of 17%. Therefore, to increase this conversion rate, several research questions can be asked:

- How can detection techniques be improved?
- How can selections be better carried out in the youth categories?
- What variables, other than immediate performance, can contribute to better estimating potentials?

OBJECTIVES

Therefore, in order to best address these questions, the objectives are outlined as follows:

- 1) To identify a relative age effect among French young swimmers and athletes and provide a rebalancing approach to better assess their performances in relation to their exact age.

Assumption: Older athletes relative to their age category will achieve better performances than their younger counterparts.

- 2) To measure the impact of relative age on the dropout rate of young French swimmers.

Assumption: Relative age has a negative impact on dropout rates, as younger swimmers within the age category are more prone to dropping out compared to their relatively older counterparts.

- 3) To analyze the relationship between maturation and performances achieved at the French Junior Swimming Championships.

Assumption: The more mature a swimmer is, the more likely he will perform well.

- 4) To measure the conversion rates between the youth, junior, and senior categories and major international competitions among French swimmers.

Assumption: Few young elite swimmers manage to transition to the senior elite level. Conversely, those who succeed at the senior level have not necessarily been at the elite level in the lower age categories.

Altogether, these sub-objectives respond to the main thesis purpose: **measure and implement methods to consider relative and biological ages in detection and selection processes.**

METHODS

Data

Swimming

To address the objectives in swimming, a retrospective database was constructed using data from competitions of all levels: local, departmental, regional, national, continental, and international. As soon as a swimmer achieved a performance within a regulated competition, his information was entered into the database. This required the swimmer to have a license and engage in club-based swimming. Thus, through the French Swimming Federation, we were able to obtain the following variables for each competitor and for each performance since 2001:

- Swimmer's identifier
- Date of birth
- Sex
- Club
- Department
- Region
- Performance identifier
- Performance time
- Event
- Pool length
- Competition date

The events covered were as follows:

- Freestyle: 50m, 100m, 200m, 400m, 800m and 1500m
- Backstroke: 50m, 100m, 200m
- Breaststroke: 50m, 100m, 200m
- Butterfly: 50m, 100m, 200m
- Individual medley: 100m, 200m and 400m

Maturation

In an effort to address the issues surrounding biological age, a data collection was initiated during the 2022 French Junior Swimming Championships. In addition to the data collected during competitions (as mentioned above), mass, seated height, and standing height data were gathered for each swimmer.

Track-and-field

In track-and-field, the method is similar except for the start date of data collection, which was set in 2010. The events covered are:

- Sprints: 100m, 200m, 400m
- Hurdles: 400m, 110m for males and 100m for females
- Middle-distance races: 800m, 1000m
- Jumps: pole vault, high jump, long jump, triple jump
- Throws: shot put, hammer throw, javelin throw, discus throw.

Statistical analysis

The statistical analyses, established according to the studies' specific goals, are detailed in each corresponding section.

Research ethics

Our data are provided by the French Swimming and Track and field Federations. All data are reported anonymously. Data collection complies with the General Data Protection Regulations (RGPD) applied in the European Union. The IRMES scientific committee designed and monitored this study. The ethics panel of CSMF (Conseil Scientifique, Médical et de Formation) from INSEP (Institute National du Sport de l'Expertise et de la Performance) approved the protocol. The Commission Nationale de l'Informatique et des Libertés (governing office supervising data utilization in France, CNIL n° 2223498) approved the use of retrospective data obtained from public sources.

SCIENTIFIC CONTRIBUTION

RELATIVE AGE EFFECT IN SWIMMING

Study 1

CORRECTIVE ADJUSTMENT METHODS FOR RELATIVE AGE EFFECTS ON FRENCH YOUNG SWIMMERS' PERFORMANCES

Introduction and objective

Selection processes in sports are organized by age categories [220]. However, athletes born right after the cutoff date are almost one (in case of annual selections) or two categories older (if selections occur every two years) than the ones born shortly before the cutoff date [120]. This variation inside a same age-category can lead to an asymmetric repartition of athletes with respect to birth months, with an overrepresentation of those born at the beginning of the competitive year. This phenomenon is called the Relative Age Effect (RAE) [120]. The RAE has been shown for both sexes [221] and in multiple sports like ice hockey, football, volley-ball, basket-ball, baseball, rugby, tennis, track-and-field [9] and swimming [8], [85], [106], [222]. This phenomenon is commonly transient: exacerbated in the youngest categories, it wanes at older ages [8], [47]. Indeed, a study conducted within FC Barcelona on popular team sports from U10 to senior category showed that the RAE is lower among seniors, in male's basketball, handball, futsal and football as well as in seniors female's football than in younger categories. Another study among young top-level swimmers has shown that there was no RAE at 16 whereas, there was a medium effect size at 13. The RAE also exhibits potentiation effects with level of competitiveness : the higher the level, the greater the effect [8].

The RAE generates biases. First, the difference in age, which may be as large as 365 days for a one-year category (or 730 days for a two-year category), generates differences in physical, anthropometric and life experience. These differences provide a significant advantage during selections [9], [223], [224]. Second, selection processes are oriented toward current performance level rather than the potential one, *ie.* the future performances [225]. Third, RAE also directly acts on athlete's motivation. Lack of performance can lead to a decline in

motivation among athletes and in some cases to dropout. [85], [226]: among the underlying causes of dropout in sports, RAE and birth quarters play important roles [30], [227], [228].

Solutions have already been settled to compensate for RAE: Corrective adjustment procedures were constructed from the regressed relationship between chronological age and objective performance measures in swimming [8], [104], [223], track-and-field [99] and ski [229]. Romann and Cobley determined the regression coefficient between performance time and relative age in Australian 100m Freestyle [8]. These studies removed RAE by verifying that the proportions in the birth quarters were not significantly different, but they did not reveal the impact of the rebalancing methods on the individual readjusted performances. For swimmers and coaches, assessing rebalanced individual performance could reduce the inequalities caused by age differences, improve motivation and participation in swimming and also build on the potential that resides in each individual.

The aims of the present study were: 1) to measure the presence of RAE in all individual swimming events and levels of competitiveness; 2) to determine and apply a corrective adjustment method for all events and age categories; 3) to rebalance the individual potential performance of athletes considering the existing RAE weighted by age category and event; and 4) to reveal the potential readjusted performances.

Methods

Studied population

The dataset is composed of French female and male swimmers aged 10 to 18 years old. All swimmers competed at least once between 2000 and 2019 at a local, departmental, regional, national or international level in 25 meters or 50 meters swimming pools. The included events were 50m, 100m, 200m, 400m, 800m, 1500m Freestyle, 50m, 100m, 200m Backstroke, Breaststroke, Butterfly, 200m and 400m Individual Medley. Birth date, competition date, performance in seconds, stroke, size of pool and sex data were collected for each swimmer.

Each swimmer was present in the dataset, with his/her best performance appearing once per age category. The exact age of each swimmer at the time of a competition was calculated as the difference between the competition date and the birthdate. The relative age gap was defined by the time separating the last birthday and the competition date. It could be seen here as a time indicator in months depending on the exact age when comparing multiple swimmers.

Identifying the Relative Age Effect

Swimmers' quarters of birthdate (Q1: born in January-March, Q2: April-June, Q3: July-September, and Q4: October-December) were created. The Top10%, Top25%, Top50%, and the all swimmers' (Top100%) performance groups were created. Chi-square tests of adequacy to a uniform law were used to assess the significance of the different distributions among birth quarters; odds ratios were computed to compare the proportion of swimmers born in the first and last quarters. Significance thresholds were set at $\alpha = \{0.1, 0.05, 0.01\}$ (respectively *, **, *** in the results section).

Corrective adjustment method

Linear regressions at all ages, for all events were run between the relative age gap and the performance mean. This method by age category was set up to quantify the RAE by age category, event and sex. Relative age gap was considered as the explicative variable to remove RAE linked to the competition dates. The calculated slope regression coefficient was then used to rebalance performance times and compare all of them at the exact same age. To calculate this time, the slope coefficient was multiplied by the time separating the competition date and the next birthday. As competitions were held all year through, the relocated performance had to be independent from the birthdate and competition date. This calculated time was then removed from the original time to obtain the adjusted performance time. A second linear regression between the relative age gap and the mean of adjusted performances was computed to test if the regression coefficient became zero (if not, the readjustment treatment would not be effective).

$$T_{adj} = T_0 - c * m$$

T_{adj} : adjusted performance time

T_0 : initial performance time

c : slope coefficient

m : time until the next birthday in days

To test the relocation methods, swimmers with two performances in a same year of age were considered. The two performances were separated by at least 6 months because we considered this period as sufficient to generate a progression. Relocation methods were applied to the first

performance while considering the age difference between first and second performance. The relocated first performance was therefore obtained from the first performance, the rebalancing coefficient and the time delta separating the two performances.

$$T_r = T_1 - c * (T_2 - T_1)$$

T_r : rebalanced performance time

T_1 : initial performance time

T_2 : second performance time

c : slope coefficient

The Kolmogorov-Smirnov test was applied to check for normal distribution. As the sample did not follow the normal distribution hypothesis, a non-parametric Friedman test was performed to detect a significant difference between the three types of performance. We assumed the null hypothesis that the three types of performance follow the same distribution. For each age-group, it was not the case meaning that there was one type of performance that was different from the other ones. Therefore, a Wilcoxon test with Bonferroni correction (with the alpha value adjusted) was performed for each pair of possible performances to reveal which performance type was significantly different from the others.

All statistical analyses were performed using Python (version 3.8.5; Python Software Foundation, Delaware, United States).

Results

Identifying the Relative Age Effect

1 343 095 performances in 50m pools (48.93% male, 51.07% female) and 3 996 256 performances in 25m pools (48.13% male, 51.87% female) were analyzed. When comparing the proportions born in Q2, Q3 and Q4, the proportion born in Q1 is always higher than the others. For example, in male breaststroke (50m pools), 31.4%, 31.34% and 31.56% were born during Q1 for 50m, 100m, 200m events respectively, vs 18.73%, 18.73% and 18.92% during Q4 ($p < 0.01$). The distribution of birth quarters according to age category and levels of competitiveness are showed on **Table 2**. The proportion of athletes born in Q1 is significantly higher than in all other quarters. Except for 13 years old category among "All", proportions decrease from the first quarter to the last one for each age category. As the level of

competitiveness increases, the proportion within the first quarter of birth is greater, to the detriment of the fourth quarter, as indicated by ORs. Indeed, for 'All', the OR between Q1 and Q4 is maximal for the youngest category, with 1.99. However, for 'top10%', the OR oscillates between 3.59 (17 years old) and 7.85 (12 years old). This means that it is at least 3.59 times more likely to find a swimmer born in Q1 than in Q4 in the 'top10%' among the 17 years old swimmers. An overview of the birth quarters distribution for each male and female event in 50m and 25m pools respectively is presented on **Table 3** (supporting information) and **Table 4** (supporting information).

Age category	Top %	Total	Q1 (%)	Q2 (%)	Q3 (%)	Q4 (%)	χ^2	p-value	OR	p	95% CI
10	100	4439	1400 (31.54)	1176 (26.49)	1029 (23.18)	834 (18.79)	154.26	***	1.99	**	[1.79 ; 2.22]
11	100	6201	1838 (29.64)	1627 (26.24)	1480 (23.87)	1256 (20.25)	116.24	***	1.66	**	[1.51 ; 1.82]
12	100	8720	2692 (30.87)	2296 (26.33)	2054 (23.56)	1678 (19.24)	249.30	***	1.87	**	[1.73 ; 2.02]
13	100	10723	3282 (30.61)	2625 (24.48)	2659 (24.8)	2157 (20.12)	238.51	***	1.75	**	[1.63 ; 1.88]
14	100	13358	4136 (30.96)	3542 (26.52)	3177 (23.78)	2503 (18.74)	419.69	***	1.95	**	[1.83 ; 2.08]
15	100	15460	4771 (30.86)	4274 (27.65)	3503 (22.66)	2912 (18.84)	524.55	***	1.92	**	[1.82 ; 2.03]
16	100	13385	3935 (29.4)	3796 (28.36)	3071 (22.94)	2583 (19.3)	360.77	***	1.74	**	[1.64 ; 1.84]
17	100	11657	3290 (28.22)	3299 (28.3)	2662 (22.84)	2406 (20.64)	209.72	***	1.51	**	[1.43 ; 1.6]
10	50	2219	791 (35.65)	590 (26.59)	479 (21.59)	359 (16.18)	182.27	***	2.87	**	[2.46 ; 3.34]
11	50	3100	1100 (35.48)	842 (27.16)	657 (21.19)	501 (16.16)	256.92	***	2.85	**	[2.51 ; 3.24]
12	50	4360	1636 (37.52)	1147 (26.31)	935 (21.44)	642 (14.72)	482.66	***	3.48	**	[3.11 ; 3.89]

13	50	5361	1968 (36.71)	1332 (24.85)	1243 (23.19)	818 (15.26)	504.64	***	3.22	**	[2.91 ; 3.57]
14	50	6679	2415 (36.16)	1846 (27.64)	1474 (22.07)	944 (14.13)	689.62	***	3.44	**	[3.14 ; 3.77]
15	50	7730	2759 (35.69)	2208 (28.56)	1642 (21.24)	1121 (14.5)	777.19	***	3.27	**	[3.01 ; 3.55]
16	50	6692	2234 (33.38)	1937 (28.95)	1457 (21.77)	1064 (15.9)	479.35	***	2.65	**	[2.43 ; 2.89]
17	50	5828	1860 (31.91)	1662 (28.52)	1253 (21.5)	1053 (18.07)	280.90	***	2.13	**	[1.95 ; 2.33]
10	25	1109	413 (37.24)	288 (25.97)	241 (21.73)	167 (15.06)	115.47	***	3.35	**	[2.69 ; 4.18]
11	25	1550	581 (37.48)	430 (27.74)	310 (20.0)	229 (14.77)	181.62	***	3.46	**	[2.89 ; 4.14]
12	25	2180	899 (41.24)	557 (25.55)	440 (20.18)	284 (13.03)	375.42	***	4.69	**	[4.01 ; 5.48]
13	25	2680	1127 (42.05)	632 (23.58)	595 (22.2)	326 (12.16)	498.89	***	5.24	**	[4.53 ; 6.06]
14	25	3339	1322 (39.59)	920 (27.55)	697 (20.87)	400 (11.98)	542.27	***	4.82	**	[4.22 ; 5.5]
15	25	3865	1503 (38.89)	1113 (28.8)	766 (19.82)	483 (12.5)	603.64	***	4.46	**	[3.96 ; 5.02]
16	25	3346	1180 (35.27)	977 (29.2)	697 (20.83)	492 (14.7)	329.79	***	3.16	**	[2.79 ; 3.58]
17	25	2914	993 (34.08)	832 (28.55)	615 (21.11)	474 (16.27)	217.33	***	2.66	**	[2.34 ; 3.03]
10	10	443	183 (41.31)	122 (27.54)	84 (18.96)	54 (12.19)	83.82	***	5.07	**	[3.58 ; 7.18]
11	10	620	244 (39.35)	184 (29.68)	118 (19.03)	74 (11.94)	107.69	***	4.79	**	[3.56 ; 6.44]
12	10	872	414 (47.48)	207 (23.74)	161 (18.46)	90 (10.32)	266.83	***	7.85	**	[6.13 ; 10.05]
13	10	1072	499 (46.55)	237 (22.11)	225 (20.99)	111 (10.35)	301.57	***	7.54	**	[6.0 ; 9.47]

14	10	1335	542 (40.6)	366 (27.42)	273 (20.45)	154 (11.54)	240.93	***	5.24	**	[4.25 ; 6.46]
15	10	1546	621 (40.17)	443 (28.65)	306 (19.79)	176 (11.38)	281.95	***	5.23	**	[4.31 ; 6.34]
16	10	1338	482 (36.02)	403 (30.12)	276 (20.63)	177 (13.23)	163.46	***	3.69	**	[3.02 ; 4.51]
17	10	1165	416 (35.71)	354 (30.39)	239 (20.52)	156 (13.39)	139.13	***	3.59	**	[2.9 ; 4.44]

Table 2: Birth quarters distribution according to age and level of competitiveness of 50m Freestyle male swimmers in 50m pool

(Top %: Top percentage, N: number of observations, Q1-4: birth quarters 1 to 4, χ^2 : Chi-Square value, ***: $P < 0.01$, **: $P < 0.05$, OR: odds ratios between Q1 and Q4, 95% CI: 95% Confidence Interval.)

Corrective adjustment method

The linear relationship between the performance mean (in seconds) and the relative age gap at each age between 10 and 16 years old in 50m Freestyle male swimmers in 50m pools is displayed on **Figure 9**. The slope coefficient is negative at all ages: *ie.* in average, older swimmers are faster in all age categories. For example, in 10-years-old category, each day of relative age gap provides a performance reduction of 0.011 second. This can be translated into a 4 seconds gap for a 365 days difference in birthdates (being born on January 1st vs December 31st). It is worthwhile to underline an order of magnitude in the decreasing evolution of the slope coefficient: from -0.013 seconds per day in 11 years old group to -0.002 per day in 15 years old group.

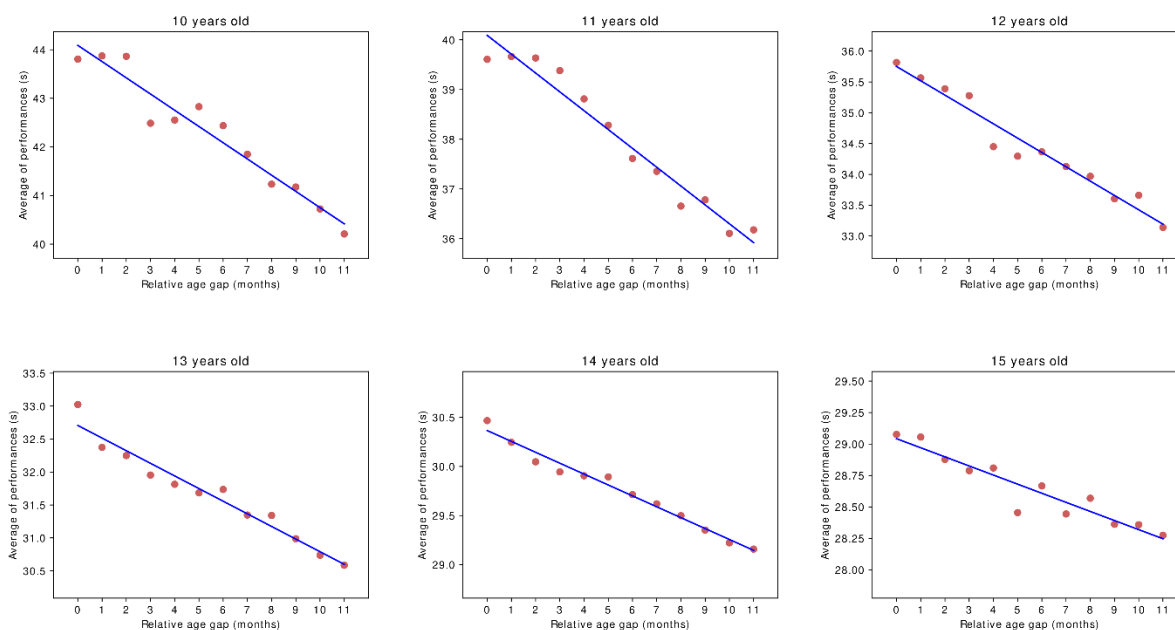


Figure 9: Performance means and relative age gap by age on 50m Freestyle male swimmers in 50m pools for 10-years-old to 15-years-old categories.

Swimmers' performances for all 10-years-old swimmers up to 16-years-old swimmers before applying the rebalancing method are represented on the left-hand side of **Figure 10**. The performances improve over time in a same-age category but as the absolute value of the balancing coefficient decreases, performances are less rebalanced year-by-year. On the right-hand side of **Figure 10**, rebalanced performance times are illustrated. We note that the 10 Best post rebalancing method is composed by new swimmers who are younger in their age categories. Indeed, the number of swimmers present in both 10 Best is low, as indicated by the stability rate (2, 2, 3 respectively for 10-years-old, 11-years-old and 12-years-old categories).

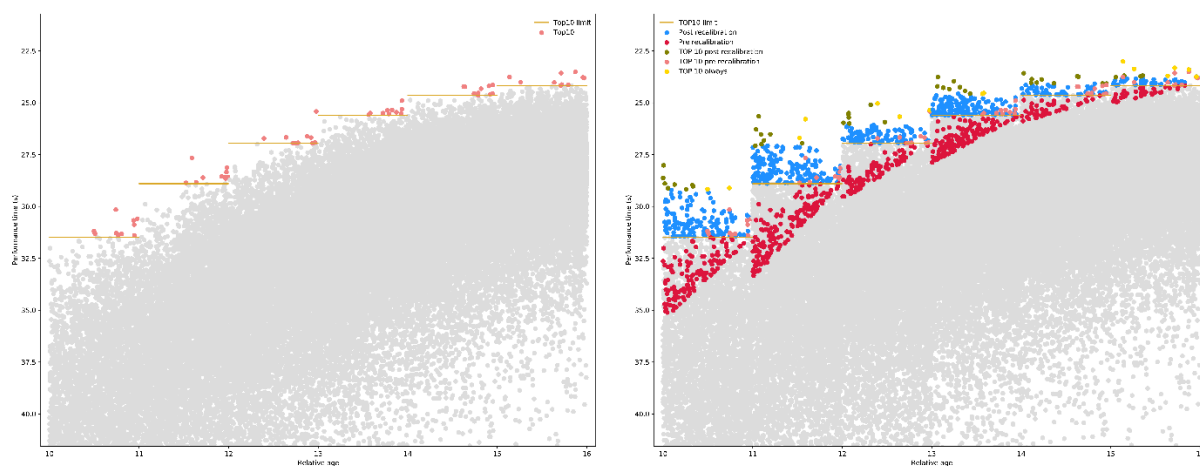


Figure 10: Application of rebalancing performances method on 50m male Freestyle between 10 and 16 years old.

On the left-hand side, time performances pre-recalibration between 10 and 16 years old on 50m Freestyle male swimmers in 50m pool. Horizontal bars (gold) in each age represent the threshold for the 10 Best performances (pink points). On the right-hand side, time performances post-recalibration between 10 and 16 years old on 50m Freestyle male swimmers in 50m pool. Horizontal bars in each age still represent the threshold for the 10 Best performances pre-recalibration. Three types of performances constitute the new 10 Best performances: the ones in the 10 Best pre and post-recalibration (golden points), the ones in the 10 Best only pre-recalibration (and present on the previous graph, pink points) and the ones in the 10 Best only post-recalibration (green points). The blue points are those above the threshold (10th performance) after recalibration and the red points below the threshold represent the blue and green points before recalibration. The rest of the points (grey points) illustrate the other recalibrated points that are below the threshold.

'All' swimmers' first, rebalanced and second performance times are represented for 10 years old to 15 years old categories (**Figure 11**). All swimming times decreased with age generating a decrease in the confidence intervals. Once the Wilcoxon test was executed, we did not find any significant difference between rebalanced and second performance times for the 10 years old, 11 years old, 12 years old, 14 years old and 15 years old categories. Indeed, for these categories, the average of relocated first performances are respectively 39.47, 35.15 and 32.28 seconds and the average of second performances are 39.06, 35.05 and 32.06 seconds.

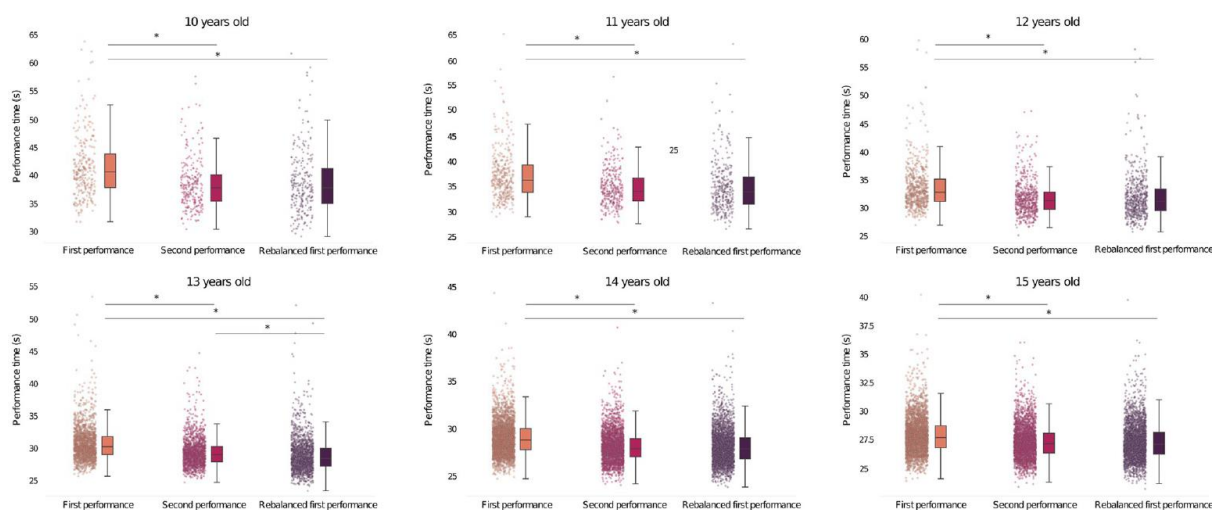


Figure 11: Statistical comparison of first, second and relocated performances.

*: significant mean performance difference ($p < 0.01$)

Discussion

This study reveals RAE in French male and female swimmers in all types of swimming events from the 10 years old to the 17 years old categories. The RAE increases with the level of performance but tends to decrease in the older categories. A new corrective adjustment procedure has been implemented to rebalance the performance of young French swimmers. It has been tested on real performances, which allowed to validate this new method.

In our results, the proportion of swimmers born in the last semester (S2) is constantly lower than the proportion of the ones born during the first semester (S1). For example, at 12, 57.2% of male Freestyle swimmers were born during the first half of the year. This is in line with Cobley et al. [8] who studied Australian swimmers between 13 and 16 years, by level of competitiveness, but with a smaller sample. The largest difference between the first and second birth semester was found among the top 10%. Indeed, the proportion for the age of 13, 14, 15 and 16 were for the first semester 80%, 78.6%, 85% and 63.7% respectively. This unequal distribution is also present in Costa et al. [106] where they looked at the top 50 Portuguese male and female swimmers in each event born between 1992 and 1998 and aged between 12 and 18 years. The authors showed that those born in S1 represent 65.08% (13 years old), 67.80% (14 years old), 63.08% (15 years old), while 34.92% (13 years old), 32.20% (14 years old) and 36.92% (15 years old) of the population were born in S2. In this study, it can be seen

that the proportion born in the last semester is almost equal to the proportion born in the first quarter.

Among female swimmers, in this same study, 43.11% of the 12 years old category was born in Q1 compared to 9.13% in Q4. In our analysis, in female swimmers, RAE is also present in all swimming events. Abbott et al. [104] identified RAE among Australian female breaststroke events (100m and 200m) between 12 and 14 years old with the inclusion criterion of having performed at least 5 times between 1999 and 2017 and having achieved a national level qualifying time in the events considered. Globally, as much as the level of competitiveness increases, RAE impact increases as well as the proportion of born in Q1. Indeed, for the 13 years age-group, in 200m Breaststroke, this proportion stands at 34.49% for 'all', 44.44% for top25% and 50.00% for top10%. In our findings, for a same age category, when observing the evolution of birth quarters repartition, it is worth noticing that the proportion of swimmers born in Q4 decreases as the competitiveness level increases. Our study exhibits greater effects with the level of competitiveness in accordance with previous studies [8].

Indeed, our technique is different from that used by Cobley et al.[8]: even if the progression rates are not linear [180], [230], we have chosen to run linear regressions on each age category. Having a unique coefficient for each age category allows the coefficients to be independent of the previous and next age categories. In previous studies [104] authors applied a polynomial regression, but our aim was here to capture the importance of RAE within each category and not to have it affected by the performance of younger or older age categories.

Then, the novelty of this study lies mainly in the method, which does not only serve to rebalance the RAE but to adjust the performance of each swimmer according to the importance of the RAE within his/her category, and also to distance, stroke and sex. This allows all swimmers in the same category to be compared more objectively. Also, this is the first study to propose a rebalancing method on more than 5 million data using the exhaustivity of the competitions between 2000 and 2019, from the local competition level to the international one.

In our regressions, we observe a negative relationship that we can interpret as follows: in average, in a same-age category, the older the swimmer, the faster the performance time. This goes in the direction of the 'maturation-selection' hypothesis by Cobley [9] where the older ones have higher probabilities to be selected in representative teams because of the relative advantage associated to age differences. In the rebalancing procedures, swimmers who compose the new 10 Best are relatively young and are located at the beginning of their year of

age. This seems logical because they benefit from a larger rebalancing coefficient. As the coefficient decreases, while age increases, we observe that the performances are less rebalanced and the 10 Best become more stable.

However, when relocating according to the competitiveness level, the performances dispersion is reduced, the population is smaller and so is the calibration coefficient. This is why the performances in the top 10% are poorly rebalanced. It is also possible that these performances occur when swimmers are relatively old in their age category, which is another reason for low rebalancing. This type of relocations has been previously shown in the study of De Larochelambert et al. [229], which confirmed the presence of a RAE in French alpine skiing with calibration coefficients decreasing with age.

This method rebalances performances in order to reveal the potential of each swimmer as opposed to previous studies which aimed at canceling RAE. Other variables should then be integrated, such as anthropometric variables, or power indices. In fact, swimming personal best times were found to be correlated with biometrics, such as height and weight [231], hand, forearm or torso lengths [232], or with muscle power assessed through standing broad jump or 30m running sprint time [233].

Williams et al. [234] have highlighted four groups of potential predictors of adult success in football: physical, psychological, skill and sociological variables. In addition, they specially focus on maturation, life events (as birth place or information about siblings), developmental environment and external (non-sporting) environment. Indeed, performance prediction is a complex process. Potential identification should progressively integrate most of these co-factors.

Conclusion and practical applications

We demonstrate the presence of relative age effect in both male and female French young swimmers. This highlights the importance of a relative age effect, which increases with competitiveness level. A corrective adjustment procedure allows to more objectively monitor the performance realized by each swimmer with respect to chronological age. This method may allow for a better understanding of each swimmer performance and improve the selection process in the early quest for high potentials. If used on the field, this method can help overcome differences in the chronological age of swimmers and can be used as a decision

support tool for coaches by allowing them to visualize possible differences among swimmers within the same age category.

Supporting information

Event	Total	Q1 (%)	Q2 (%)	Q3 (%)	Q4 (%)	χ^2	p-value	OR	95% CI
50 Freestyle Male 50m	86397	25522 (29.54)	23381 (27.06)	20369 (23.58)	17125 (19.82)	1856.32	***	1.70	[1.66 ; 1.74]
100 Freestyle Male 50m	83474	24654 (29.53)	22551 (27.02)	19682 (23.58)	16587 (19.87)	1768.21	***	1.69	[1.65 ; 1.73]
200 Freestyle Male 50m	49723	14914 (29.99)	13677 (27.51)	11549 (23.23)	9583 (19.27)	1335.95	***	1.79	[1.73 ; 1.85]
400 Freestyle Male 50m	41726	12735 (30.52)	11161 (26.75)	9829 (23.56)	8001 (19.18)	1160.77	***	1.85	[1.79 ; 1.92]
800 Freestyle Male 50m	9409	2637 (28.03)	2638 (28.04)	2246 (23.87)	1888 (20.07)	165.61	***	1.55	[1.45 ; 1.66]
1500 Freestyle Male 50m	10862	3108 (28.61)	2984 (27.47)	2599 (23.93)	2171 (19.99)	197.46	***	1.60	[1.5 ; 1.71]
50 Backstroke Male 50m	48304	14451 (29.92)	13075 (27.07)	11210 (23.21)	9568 (19.81)	1132.71	***	1.73	[1.68 ; 1.79]
100 Backstroke Male 50m	42501	12540 (29.51)	11525 (27.12)	10013 (23.56)	8423 (19.82)	912.97	***	1.69	[1.63 ; 1.75]
200 Backstroke Male 50m	20044	5694 (28.41)	5639 (28.13)	4698 (23.44)	4013 (20.02)	390.11	***	1.59	[1.52 ; 1.66]
50 Breaststroke Male 50m	44670	14028 (31.4)	12124 (27.14)	10151 (22.72)	8367 (18.73)	1609.44	***	1.99	[1.92 ; 2.06]
100 Breaststroke Male 50m	38898	12190 (31.34)	10482 (26.95)	8940 (22.98)	7286 (18.73)	1358.86	***	1.98	[1.91 ; 2.05]
200 Breaststroke Male 50m	16783	5297 (31.56)	4523 (26.95)	3787 (22.56)	3176 (18.92)	602.23	***	1.98	[1.87 ; 2.09]
50 Butterfly Male 50m	55185	16618 (30.11)	14976 (27.14)	12833 (23.25)	10758 (19.49)	1414.36	***	1.78	[1.73 ; 1.83]
100 Butterfly Male 50m	35630	10659 (29.92)	9724 (27.29)	8406 (23.59)	6841 (19.2)	926.90	***	1.80	[1.73 ; 1.87]
200 Butterfly Male 50m	10972	3072 (28.0)	3025 (27.57)	2763 (25.18)	2112 (19.25)	213.75	***	1.63	[1.53 ; 1.74]
200 Individual Medley Male 50m	49072	15174 (30.92)	13281 (27.06)	11350 (23.13)	9267 (18.88)	1574.81	***	1.92	[1.86 ; 1.98]
400 Individual Medley Male 50m	13542	3999 (29.53)	3780 (27.91)	3188 (23.54)	2575 (19.01)	362.70	***	1.78	[1.68 ; 1.89]
50 Freestyle Male 25m	207650	58276 (28.06)	55406 (26.68)	48978 (23.59)	44990 (21.67)	2104.14	***	1.41	[1.39 ; 1.43]
100 Freestyle Male 25m	199379	55853 (28.01)	53005 (26.59)	47298 (23.72)	43223 (21.68)	1934.40	***	1.41	[1.39 ; 1.43]
200 Freestyle Male 25m	123781	36460 (29.46)	33041 (26.69)	28544 (23.06)	25736 (20.79)	2187.96	***	1.59	[1.56 ; 1.62]
400 Freestyle Male 25m	111226	31888 (28.67)	30405 (27.34)	26009 (23.38)	22924 (20.61)	1815.43	***	1.55	[1.52 ; 1.58]
800 Freestyle Male 25m	50600	14716 (29.08)	13937 (27.54)	11709 (23.14)	10238 (20.23)	998.26	***	1.62	[1.57 ; 1.67]
1500 Freestyle Male 25m	33991	9889 (29.09)	9126 (26.85)	8024 (23.61)	6952 (20.45)	581.81	***	1.60	[1.54 ; 1.66]
50 Backstroke Male 25m	146901	42180 (28.71)	39429 (26.84)	34149 (23.25)	31143 (21.2)	2038.47	***	1.50	[1.47 ; 1.53]
100 Backstroke Male 25m	124810	34858 (27.93)	33594 (26.92)	29702 (23.8)	26656 (21.36)	1346.18	***	1.43	[1.4 ; 1.46]
200 Backstroke Male 25m	54809	15538 (28.35)	14913 (27.21)	12847 (23.44)	11511 (21.0)	756.73	***	1.49	[1.45 ; 1.53]
50 Breaststroke Male 25m	145682	42486 (29.16)	38905 (26.71)	33554 (23.03)	30737 (21.1)	2292.17	***	1.54	[1.51 ; 1.57]
100 Breaststroke Male 25m	124195	35389 (28.49)	33302 (26.81)	29129 (23.45)	26375 (21.24)	1592.47	***	1.48	[1.45 ; 1.51]
200 Breaststroke Male 25m	53634	15784 (29.43)	14655 (27.32)	12383 (23.09)	10812 (20.16)	1117.96	***	1.65	[1.6 ; 1.7]
50 Butterfly Male 25m	142492	41442 (29.08)	38451 (26.98)	33107 (23.23)	29492 (20.7)	2407.93	***	1.57	[1.54 ; 1.6]
100 Butterfly Male 25m	96668	27719 (28.67)	26285 (27.19)	22812 (23.6)	19852 (20.54)	1554.10	***	1.56	[1.53 ; 1.59]
200 Butterfly Male 25m	37322	10754 (28.81)	10327 (27.67)	8834 (23.67)	7407 (19.85)	746.55	***	1.63	[1.57 ; 1.69]
100 Individual Medley Male 25m	96227	28522 (29.64)	25856 (26.87)	22474 (23.36)	19375 (20.13)	1978.64	***	1.67	[1.63 ; 1.71]
200 Individual Medley Male 25m	111731	32197 (28.82)	30389 (27.2)	26214 (23.46)	22931 (20.52)	1868.37	***	1.57	[1.54 ; 1.6]
400 Individual Medley Male 25m	62452	18508 (29.64)	16978 (27.19)	14519 (23.25)	12447 (19.93)	1374.79	***	1.69	[1.64 ; 1.74]

Table 3: Birth quartiles distribution in male individual events in 25 and 50m pool for all age categories between 10 and 18 years old

(Q1-4: birth quarters, χ^2 : Chi-Square value, ***: $P < 0.01$, OR: odds ratios between Q1 and Q4, 95% CI: 95% Confidence Interval.)

Event	Total	Q1 (%)	Q2 (%)	Q3 (%)	Q4 (%)	χ^2	p-value	OR	95% CI
50 Freestyle Female 50m	91115	26976 (29.61)	24860 (27.28)	21067 (23.12)	18212 (19.99)	2007.74	***	1.68	[1.64 ; 1.72]
100 Freestyle Female 50m	85181	25105 (29.47)	23220 (27.26)	19907 (23.37)	16949 (19.9)	1833.08	***	1.68	[1.64 ; 1.72]
200 Freestyle Female 50m	50503	14826 (29.36)	14035 (27.79)	11838 (23.44)	9804 (19.41)	1220.51	***	1.73	[1.68 ; 1.78]
400 Freestyle Female 50m	40807	12056 (29.54)	11183 (27.4)	9629 (23.6)	7939 (19.45)	965.44	***	1.74	[1.68 ; 1.8]
800 Freestyle Female 50m	14522	4115 (28.34)	4035 (27.79)	3537 (24.36)	2835 (19.52)	286.44	***	1.63	[1.54 ; 1.72]
1500 Freestyle Female 50m	3660	1052 (28.74)	1011 (27.62)	877 (23.96)	720 (19.67)	73.72	***	1.65	[1.47 ; 1.85]
50 Backstroke Female 50m	54841	16470 (30.03)	14854 (27.09)	12694 (23.15)	10823 (19.74)	1334.28	***	1.75	[1.7 ; 1.8]
100 Backstroke Female 50m	48001	14300 (29.79)	13067 (27.22)	11244 (23.42)	9390 (19.56)	1150.99	***	1.74	[1.69 ; 1.8]
200 Backstroke Female 50m	22123	6313 (28.54)	6062 (27.4)	5279 (23.86)	4469 (20.2)	376.95	***	1.58	[1.51 ; 1.65]
50 Breaststroke Female 50m	49302	15025 (30.48)	13426 (27.23)	11257 (22.83)	9594 (19.46)	1387.46	***	1.81	[1.75 ; 1.87]
100 Breaststroke Female 50m	44138	13413 (30.39)	12106 (27.43)	10014 (22.69)	8605 (19.5)	1246.03	***	1.80	[1.74 ; 1.86]
200 Breaststroke Female 50m	19784	5844 (29.54)	5427 (27.43)	4569 (23.09)	3944 (19.94)	441.55	***	1.68	[1.6 ; 1.76]
50 Butterfly Female 50m	55105	16851 (30.58)	14768 (26.8)	12747 (23.13)	10739 (19.49)	1504.18	***	1.82	[1.77 ; 1.88]
100 Butterfly Female 50m	32696	9999 (30.58)	8820 (26.98)	7749 (23.7)	6128 (18.74)	992.74	***	1.91	[1.83 ; 1.99]
200 Butterfly Female 50m	9253	2780 (30.04)	2517 (27.2)	2157 (23.31)	1799 (19.44)	237.00	***	1.78	[1.65 ; 1.92]
200 Individual Medley Female 50m	52537	15702 (29.89)	14374 (27.36)	12382 (23.57)	10079 (19.18)	1372.80	***	1.80	[1.74 ; 1.86]
400 Individual Medley Female 50m	12335	3619 (29.34)	3384 (27.43)	2940 (23.83)	2392 (19.39)	284.01	***	1.73	[1.62 ; 1.84]
50 Freestyle Female 25m	220852	62998 (28.52)	59331 (26.86)	51863 (23.48)	46660 (21.13)	2933.01	***	1.49	[1.47 ; 1.51]
100 Freestyle Female 25m	208906	59885 (28.67)	55906 (26.76)	49059 (23.48)	44056 (21.09)	2852.60	***	1.50	[1.48 ; 1.52]
200 Freestyle Female 25m	128466	37821 (29.44)	34377 (26.76)	30144 (23.46)	26124 (20.34)	2411.60	***	1.63	[1.6 ; 1.66]
400 Freestyle Female 25m	113925	33401 (29.32)	31386 (27.55)	26488 (23.25)	22650 (19.88)	2479.46	***	1.67	[1.64 ; 1.7]
800 Freestyle Female 25m	82570	23656 (28.65)	22920 (27.76)	19533 (23.66)	16461 (19.94)	1597.87	***	1.61	[1.57 ; 1.65]
1500 Freestyle Female 25m	5796	1704 (29.4)	1557 (26.86)	1340 (23.12)	1195 (20.62)	105.65	***	1.60	[1.46 ; 1.75]
50 Backstroke Female 25m	165872	48479 (29.23)	44660 (26.92)	38589 (23.26)	34144 (20.58)	2924.49	***	1.59	[1.56 ; 1.62]
100 Backstroke Female 25m	137837	39701 (28.8)	37109 (26.92)	32616 (23.66)	28411 (20.61)	2161.28	***	1.56	[1.53 ; 1.59]
200 Backstroke Female 25m	60698	17406 (28.68)	16384 (26.99)	14569 (24.0)	12339 (20.33)	978.56	***	1.58	[1.54 ; 1.63]
50 Breaststroke Female 25m	165638	48393 (29.22)	44539 (26.89)	38417 (23.19)	34289 (20.7)	2854.89	***	1.58	[1.55 ; 1.61]
100 Breaststroke Female 25m	139267	40490 (29.07)	37401 (26.86)	32166 (23.1)	29210 (20.97)	2220.95	***	1.54	[1.51 ; 1.57]
200 Breaststroke Female 25m	62187	17961 (28.88)	17099 (27.5)	14386 (23.13)	12741 (20.49)	1122.91	***	1.58	[1.54 ; 1.62]
50 Butterfly Female 25m	150183	44286 (29.49)	40782 (27.15)	34831 (23.19)	30284 (20.16)	3089.75	***	1.66	[1.63 ; 1.69]
100 Butterfly Female 25m	98374	29218 (29.7)	26576 (27.02)	22713 (23.09)	19867 (20.2)	2081.54	***	1.67	[1.63 ; 1.71]
200 Butterfly Female 25m	37546	11079 (29.51)	10277 (27.37)	8697 (23.16)	7493 (19.96)	822.28	***	1.68	[1.62 ; 1.74]
100 Individual Medley Female 25m	102246	30746 (30.07)	27630 (27.02)	23732 (23.21)	20138 (19.7)	2500.60	***	1.75	[1.71 ; 1.79]
200 Individual Medley Female 25m	124922	36149 (28.94)	34237 (27.41)	29274 (23.43)	25262 (20.22)	2327.26	***	1.61	[1.58 ; 1.64]
400 Individual Medley Female 25m	67421	19982 (29.64)	18660 (27.68)	15647 (23.21)	13132 (19.48)	1682.33	***	1.74	[1.69 ; 1.79]

Table 4: Birth quarters distribution in female individual events in 25 and 50m pool

(Q1-4: birth quarters, χ^2 : Chi-Square value, ***: $P < 0.01$, OR: odds ratios between Q1 and Q4, 95% CI: 95% Confidence Interval.)

Panel: Research in context

WHAT WERE THE ISSUES AROUND THIS SUBJECT?

Few studies have looked at the solution of rebalancing RAE and even fewer investigated performances recalibration in order to estimate potential and less to select performances that could enforce the relative age effect among young athletes.

WHAT DOES THIS STUDY ADD TO EXISTING KNOWLEDGE?

A relative age effect has been observed among young French female and male swimmers. This phenomenon is accentuated when the level of competition increases. The method employed is characterized by the use of coefficients per age category in order to capture the strength of the corresponding relative age effect for each young athlete in their specific sport and event context.

TRANSLATIONAL OUTLOOK

This is the first study on French swimmers to examine the relative age effect among all individual events. It provides an overview of the birth months distribution of young French swimmers between 10 to 18 years old. Since swimming is a sport where performance is measured in seconds, it's a good candidate for applying rebalancing methods. Calculating rebalancing coefficients for a metric sport is facilitated. In addition, it is a sport in which the events, despite their specific features for each swim, are similar. The aim is to achieve the fastest time possible.

Faced with these different criteria, the aim of study 2 is to carry out a similar analysis on the different events that make up track-and-field to detect a significant relative age effect at different ages. Track-and-field is a sport that includes sprinting, medium to long running, hurdling, jumping and throwing events. It is also a metric sport, which makes it easy to apply rebalancing methods.

RELATIVE AGE EFFECT IN TRACK-AND-FIELD

Study 2

RELATIVE AGE EFFECT IN TRACK-AND-FIELD: IDENTIFICATION AND PERFORMANCE REBALANCING

Introduction and objective

In sports, the relative age effect (RAE) is related to an over-representation of athletes born right after the cut-off date and an under-representation of those born just before the next cut-off date [26]. It shows a skewed distribution of athletes, and has been demonstrated among girls [221] and boys [235] - with a smaller effect among females - and in team sports and individual sports [235]. Indeed, in track-and-field, U18 females and males born in January or February are respectively 2 and 3 times more likely to be ranked in the Top 100 best athletes than those born at the end of the year [102]. The relative age effect creates a bias on performances, whereby athletes born close to the cut-off date have an advantage compared to their peers born 12 months or 24 months later, depending on whether it is a one-year or a two-years category. In English track and field [114] it is present in the majority of events and maximal in the U13 category - where U13 (*Under 13 years old*) represents a two-year age category composed of young athletes, who are 11 or 12 years old). Although RAE seems greater at this age, one study investigated Italian long and high jump athletes between 15 and 20 years old [236]. Only 10-25% of top level adults were already in the top level at age 16 [236]. It is possible that the RAE, with a feeling of discouragement [103] generated by non-selection, the consecutive dropouts or cumulative disadvantages (better coaching, counterparts and competition [120]) plays a role. RAE persists in track-and-field [89]: it is greater among World Youth (U17) than in Junior Track-and-field Championships [103], but decreases when sprinters get older [237] or when competitiveness increases. The effect has also been observed in another metric sport which initiates the first theoretical readjustments of this effect: swimming [8].

Solutions have already been settled to compensate for the bias induced by RAE: by focusing on organizational (e.g., rotating cut-off dates [16] or classifying athletes by maturation status

[158], [238]) or practical strategies (e.g., shirt numbering based on month age [155] or correction factor to performance results [223]). Though performance does not progress linearly with age [180], [239], corrective adjustments have been proposed with linear regressions in each age category [237]. Slope coefficients from linear regressions were used to rebalance performance [8]. Indeed, each day, week or month of difference between two athletes generates a difference in performance [8]. Quadratic equation models have been used to fit the best curve among sprinters performances: between 15 and 16.99 years old (U17), their compensating method was based on how far the age at performance was from 16 [89]. The common goal was to reduce the RAE by birth quarters distribution. A recent study [88] applied corrective adjustment procedures (CAPs) as a strategy to remove relative age effects on 689 junior Italian long jumpers. A recent study on French skiers showed that it is possible to cancel out the relative age effect through recalibration [229]. Based on a regression coefficient per age category, performances are rebalanced according to their exact age and initial performance [229]. Using the same methods, corrective adjustment procedure were applied to more objectively monitor the performance realized by each swimmer with respect to chronological age, in all events [240]. With this recalibration method, swimmers' performances were interpreted at the same exact age, in a more equitable way [240].

There is no study on the relative age effect on young French athletes to our knowledge, and even in the scientific literature, at the international level, the subject is not very explored. In the quest for top performances, records and medals at the international level, detection is the basis of this pathway [234]. The better the detection, the better the high-level athletes. This is why we try to explore all possible aspects of detection, starting with the relative age effect [235]. Thus, our aim is to study the relative age effect in French Track and Field, and to propose a corrective adjustment method to better evaluate the potential of each athlete.

Methods

Participants

The dataset was composed of French Track and Field athletes aged 12 to 22 and classified into one-year age categories, from U13 (Under 13) to U23 (Under 23). It included 189 238 male and 169 372 female performances, from athletes who competed at least once in local, regional, national or international competitions since 2009. All recorded performances conformed to

standards of the International Association of Athletics Federations and were collected by the French Track and Field Federation. Date of birth, date of competition and all performances were collected. Also, the level of competitiveness was considered as follows: 'All', 'Top50%' which corresponds to the best 50% of the age category in the event concerned and 'Top10%' which corresponds to the best 10% in an equivalent way. For both male and female, events included 100m, 200m, 400m, 800m, 1000m, 400m hurdles, shot put, discus throw, javelin throw, hammer throw, high jump, pole vault, long jump, triple jump plus 100m (for female) or 110m (male) hurdles. Other events were not considered due to lack of data in youth categories.

Analysis

All statistical analyses were performed using Python (version 3.8.5; Python Software Foundation, Delaware, United States).

Part 1: Presence of RAE

In this first part, all athletes were considered. For each of them, only the best performance was kept. Then, athletes were divided into birth quarters according to their month of birth (Q1: January, February, March, Q2: April, May, June, Q3: July, August, September, Q4: October, November, December). In order to highlight the existence of RAE within the real age categories, birth quarters distributions were compared to the French distribution of births covering the birth years of all athletes in the study [241]. Indeed, the population was distributed as follows: 178,080 (23.64%) in Q1, 185,727 (24.65%) in Q2, 198,872 (26.40%) in Q3 and 190,702 (25.31%) in Q4. A chi-square test was used to determine whether the proportions of the population are consistent with the theory, in this case the French population born on the same years.

Part 2: Rebalancing methods

In this section, athletes who were actually involved in the discipline were included, only if they performed at least 6 times over the 6 years considered, between the ages of 12 and 17. Athlete's exact age was obtained by calculating the difference between the date of birth and the competition date. Relative age gap was defined by the time delay between athlete's last birthday and competition date, as it can be interpreted as an index to quantify athlete's experience within his/her age category. Using a method similar previously employed [229], [240], linear regressions for each age group between the relative age gap and the average of

performances were computed in order to obtain the slope value “*c*”. The slope coefficient was converted into days and used to calculate the recalibrated coefficient: $r = c * d$ where “*c*” is the slope value and “*d*” the number of days until the next birthday. The recalibrated coefficient “*r*” was subtracted (in race events, measured in seconds) or added (in jumps or throws, measured in meters) to the performance in order to obtain rebalanced performances.

Part 3: Testing rebalancing methods

In order to validate our method, we kept for each athlete from the previous base, two performances of the same age category (T1 and T2) if they were separated by at least 6 months (to allow sufficient time for progression). The rebalancing method was applied to the first performance (T1) in order to obtain the rebalanced performance (T2’) using the following formula:

$$T2' = T1 - r * (dT2 - dT1)$$

dT2: exact age of realized performance in days

dT1: exact age of first performance in days

In this part, our objective was to show that the second realized performance (T2) is not statistically different from the rebalanced performance (T2’) in order to validate the rebalancing method. After checking that the data did not follow a normal distribution with the Kolmogorov Smirnov test, we used a non-parametric Friedman test to see if the three types of performance followed the same distribution.

Therefore, as it was not the case, a Wilcoxon test was performed to identify which performance was statistically different from the other two. Thus, by performing the Wilcoxon test on each possible pair (T1-T2’, T1-T2, T2-T2’), it is possible to show that: if the first performance (T1) is statistically different from the other two, it can be concluded that the other two performances (T2 and T2’) were not statistically different. Thus, if there is no statistical difference between the rebalanced performance and the realized performance, this will validate the rebalancing method.

Results

Part 1: Presence of RAE

Birth quarters distribution on the youngest age categories for 'All', 'Top50%' and 'Top10%' female and male athletes in 100m sprint is presented in **Figure 12**. For any sex or performance level, not only the distribution of athletes' birth quarters significantly differs from the French distribution of births, but also the proportion born in Q4 is lower than the proportion in any other quarter.

For U13 females, the proportion of 100m sprinters born in Q4 is 21.4%, 19.3% and 16.2% for 'All', 'Top50%' and 'Top10%' respectively. Similarly, among males, the proportion of Q1 increases considerably among U14: 27.6%, 34.4% and 43.4% for 'All', 'Top50%' and 'Top10%' respectively.

For males, the RAE is accentuated by the proportion of Q4 among U13 and U17, which are 23.2% and 19.1% respectively in the 'All' category. Among the 'Top50%' and 'Top10%', the effect is maximal in the U15 category and decreases thereafter. The distribution of birth quarters by age category for all events and sexes for 'All' and 'Top10%' is presented in the **supporting information (Figures 15-18)**, with an under-representation of athletes born in Q4 for the majority of events.

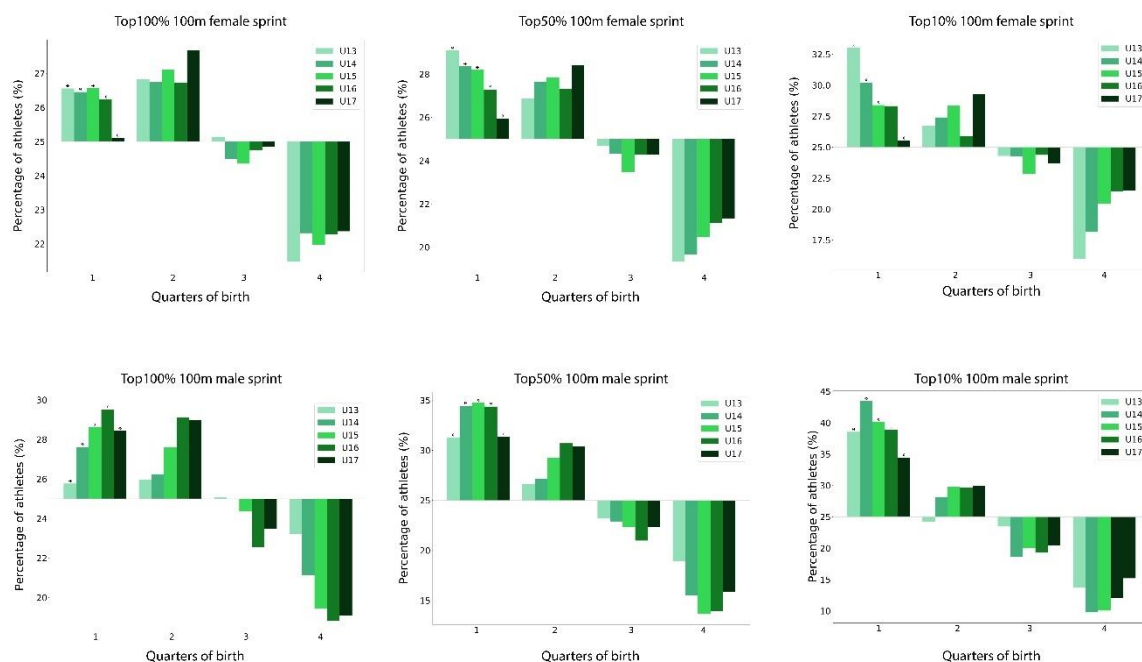


Figure 12: Birth quarters distribution according to age categories and performance level for female and male 100m sprint.

F: female, M: male, ***: $P < 0.01$

Part 2: Rebalancing methods

After running linear regressions on performance as a function of the relative age gap, the resulting coefficients are presented for 100m female and male sprint in **Table 5** and **Table 6** respectively. The coefficient is highest among the U13, regardless of sex. For females, within the same age group, there can be 564.1ms (3.875%), 141.0ms (1.0%), 47.0ms (0.3%) and 1.5ms (0.01%) of difference on average per year, quarter, month and day respectively. For males, the difference is greater, with a year, quarter, month and day generating an advantage of 931.0ms (+6.5%), 232.8ms (+1.6%), 77.6ms (+0.5%) and 2.6ms (+0.02%) respectively.

Age	Mean (s)	Δ day in ms (%)	Δ month in ms(%)	Δ quarter in ms (%)	Δ year in s (%)
U13	14,56	-1,54 (-0,01)	-47,01 (-0,32)	-141,04 (-0,97)	-0,564 (-3,87)
U14	14,10	-1,25 (-0,01)	-37,95 (-0,27)	-113,86 (-0,81)	-0,455 (-3,23)
U15	13,79	-0,71 (-0,01)	-21,67 (-0,16)	-65,00 (-0,47)	-0,260 (-1,89)
U16	13,55	-0,75 (0,01)	-22,75 (-0,17)	-68,26 (-0,50)	-0,273 (-2,01)
U17	13,37	-0,34 (-0,01)	-10,39 (-0,08)	-31,16 (-0,23)	-0,124 (-0,93)

Table 5: Mean performance differences by year, quarter, month and day, among 100m female sprinters

Δ : mean difference, ms: milliseconds, s: seconds, %: in percentage of performance mean

Age	Mean (s)	Δ day in ms (%)	Δ month in ms (%)	Δ quarter in ms (%)	Δ year in s (%)
U13	14,33	-2,55 (-0,02)	-77,58 (-0,54)	-232,75 (-1,62)	-0,931 (-6,50)
U14	13,42	-2,17 (-0,02)	-66,01 (-0,49)	-198,03(-1,48)	-0,792 (-5,90)
U15	12,74	-1,75 (-0,01)	-53,18 (-0,42)	-159,55 (-1,25)	-0,638 (-5,01)
U16	12,24	-1,29 (0,01)	-39,12 (-0,32)	-117,36 (-0,96)	-0,469 (-3,83)
U17	11,93	-0,63 (-0,005)	-19,14 (-0,16)	-57,41 (-0,48)	-229,65 (-1,93)

Table 6: Mean performance differences by year, quarter, month and day, among 100m male sprinters

Δ : mean difference, ms: milliseconds, s: seconds, %: in percentage of performance mean

Part 3: Testing rebalancing methods

The pre-rebalancing performances for females 100m for U13 to U17 categories are shown in **Figure 13A**. On the age axis, the majority of the 10-Best performances are concentrated

towards the end of the age category concerned, meaning that the most performant are the older even in a same-age category.

The rebalanced performances of the same population according to age and the initial performance is presented in **Figure 13B**. First, new potentials emerge through this rebalancing method. Indeed, there are 35, 37, 23, 18 and 22 of them, respectively at U13, U14, U15, U16 and U17 to exceed the pre-rebalancing 10-Best performances. Then, among them, rebalanced performances come to feed a new 10-Best (10-Best rebalanced). In the youth categories, this 10-Best is renewed by almost half and more stable with age.

The principle is similar for **Figures 13C** and **13D**, with pre-rebalancing and post-rebalancing performances for males 100m for U13 to U17 categories respectively. Again, the best performances before rebalancing are achieved by relatively older athletes. On the other hand, more rebalanced performances are above the 10-Best threshold. In the U15 category, 103 new athletes appear in the list, with great potential.

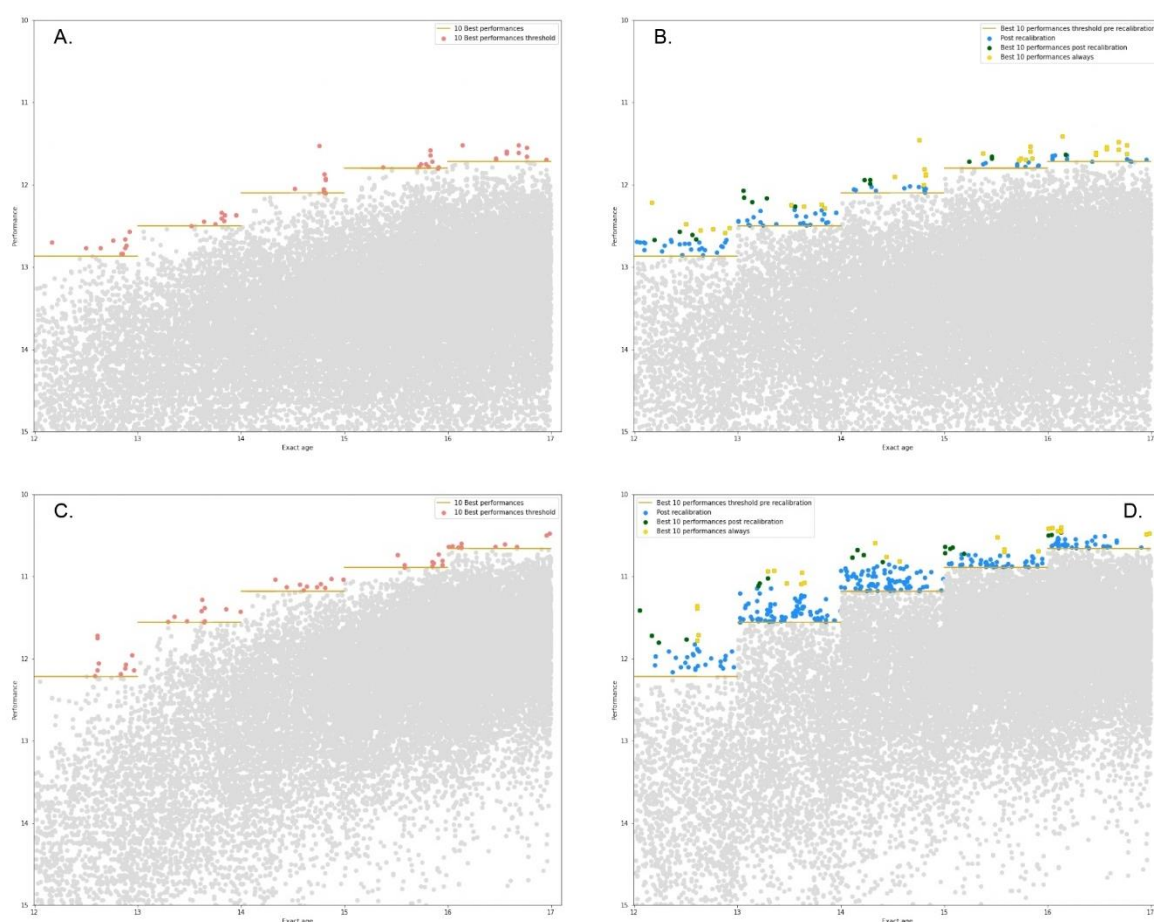


Figure 13: Application of rebalancing performances method on 100m female and male sprinters among U13 to U17 categories

A. Raw time performances among U13 to U17 categories of 100m French female sprinters. Horizontal bars (gold) in each age represent the threshold to reach the 10-Best performances (pink points). **B.** Time performances post-rebalancing among U13 to U17 categories of the same 100m French female sprinters. Performances above the threshold (but not in the 10-Best pre-rebalancing) after rebalancing are now shown in blue. The performances that were already in the 10-Best before rebalancing are in yellow. The performances that make up to the 10-Best only after rebalancing are colored in green. **C.** Raw time performances among U13 and U17 categories of 100m French male sprinters. **D.** Time performances post-rebalancing among U13 to U17 categories of the same 100m French male sprinters.

In order to validate our individual rebalancing method, we compare the rebalanced performance with the second realized performance. The difference between these two performances is shown in **Figure 14** in percentage. On average, by category, the rebalanced performance and the second performance achieved are not significantly different. As can be seen, the difference between the two types of performance is centered around zero, so there is no significant difference between the realized performance and the rebalanced performance.

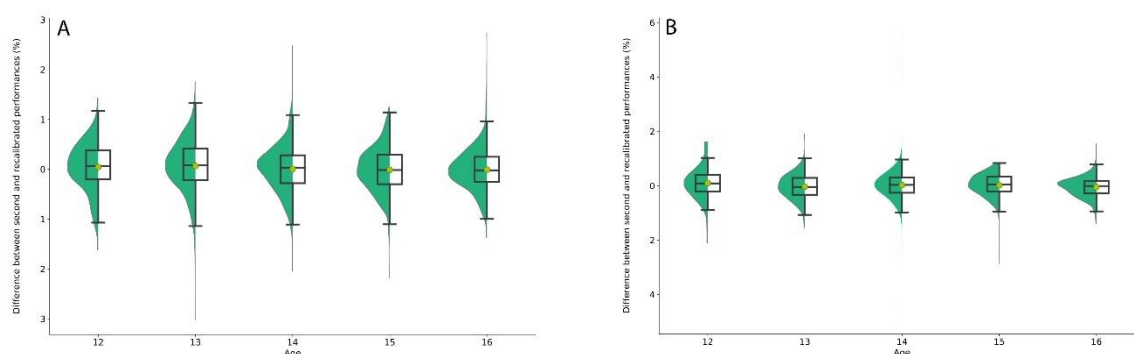


Figure 14: Validation methods of rebalanced performance times

A. Boxplot of percentage differences between rebalanced performances and second performances achieved in the female 100m of U13 to U17 categories. **B.** Boxplot of percentage differences between rebalanced performances and second performances achieved in the male 100m of U13 to U17 categories.

Discussion

This study shows a strong relative age effect among young French Track and Field athletes. A correcting method is validated to individually rebalance each athlete performance and bring out her/his potential, according to the exact age at the time of performance. Corrections are computed for all events, sexes and age categories.

An asymmetric distribution of birth quarters is shown for U13 and U17 categories among 100m male sprinters. This RAE increases with the performance level in certain age categories, particularly in the younger ones. RAE was investigated among 77 571 performance data of U13, U15, U17, U20 and senior English athletes [114]. They found that U13 male 100m sprinters were 6.3 times more likely to be born in the first trimester (Q1 vs Q4), an odds ratio that decreased with age. The probability of being born in Q1 among U15, U17, U20 and senior is 4.2, 2.6, 2.1 and 1.8 higher than in Q4, respectively. Among French throwers, the U16 category stands out with a strong over-representation of Q1. This trend was in accordance with a recent study [114], where the OR decreased after the U15. Despite the fact that the age categories include a two-year period, the authors have chosen to focus only on the last year of the age category. In our study, we chose to explore each year of the age group in view of the rebalancing method that allows for the comparison of athletes competing together. Other authors have chosen to also look at athletes in both years of the U18 and U20 age categories. Based on 642 Spanish athletes, a stronger RAE was also highlighted, measured by odds-ratio, for male U18 and U20 first year, among a restricted sample [101]. Indeed, they analyzed athletes who competed at international level between 2006 and 2014 and considered all events at once. Among 61 males U18 first year athletes involved, none was born in the fourth quarter vs. 39 in the first one. Information about selections in national teams was not provided in this study but the distribution was classified by competitiveness levels. National team members are included in the 'Top10%' ; e.g. among the U18 'Top10%' of the 110m hurdles males, 35.8% were born in the first trimester vs 13.3% in the last one.

Our results also reveal a strong RAE among female athletes in the 100m sprint, throws and jumps, enhanced by the level of performance. However, a study analysing the Swiss Talent Development Program did not find RAE among Track and Field female athletes [242]. Nevertheless, even if they distinguished two types of competitiveness levels (all teenagers between 10 and 20 years old interested in sport and the Talent Development Program level), they did not investigate RAE by age category and considered all events together. Birth quarter

distributions of female athletes were also examined on the international championships Spanish track and field athletes [101] and showed significant differences among those belonging to the first year of each category of age (U18 and U20). In the first year of the U18 category, none was born in Q4 and only one in Q3 among the selected 41 females. Among world-class junior female sprinters, RAE was also found with a larger effect in the higher levels [89]. 'All', 'Top10' and 'Top50', 100m sprinters were 1.7, 1.9 and 2.3 times more likely to be born in Q1 than in Q4. The gap was larger among 400m sprinters, for 'All', 'Top100' and 'Top50', with an odds-ratio of 1.7, 2.5 and 3.3, respectively.

Corrective adjustment procedures

By applying a rebalancing method, many individual potentials that may be lost for the future if undetected are revealed. A quadratic function was applied on 16 and 17 years old male and female athletes [89]. Using 16 and 17 years as the reference age, they corrected the performances of the 15.01 to 16.99 and 16.01 to 17.99 years old athletes, respectively. After correction, they found a smaller or no RAE among 16 year-old athletes. However, a stronger RAE was revealed among corrected performances of 17 year-old athletes, who ran the 100m and 200m. Athletes older than the reference age had their performance deteriorated, while the younger ones had their performance improved. It is then worth noticing that this study was conducted on world-class athletes, who had achieved at least 5 international performances in their career: it is therefore important to consider the competition level.

7761 sprinters (60m) between the U9 and U16 categories were considered at different performance levels [237]. After observing that the RAE increased with performance levels, the authors corrected the performances by applying a regression for all age-groups. They found that RAE was not present anymore for 'Top10%', 'Top25%' and 'Top50%' excepted for U9 and U10. This study does not investigate the same age range. As the practice of middle- and long-distances comes at later ages than sprints, we focused on earlier ages for sprints and later ages for other distances. A trend confirmed in a study [243], that spotlighted the age difference between the peaks of performance in the 100m and 6-day ultra-marathon [243]. The male performance peak was reached at 24.7 years on the 100m and at 38.1 years for ultra-marathon races. The same trend was observed for females, with a performance peak age at 25 on the 100m and at 43 for the 6-day ultra-marathon [243]. This study focuses on different age groups with respect to the considered event.

The main purpose of this study was to reveal the true potential of athletes, once the relative age effect was taken into account. Regressions were run in each age group. Coefficients of determination are high (between 0.62 to 0.94 for female, between 0.81 to 0.95 for males), showing the consistency of the results and the importance of better appreciating athlete's potentials with respect to her/his age group. It is now necessary to think in terms of age groups and not over the whole spectrum of age categories.

Correction methods have been applied in youth track-and-field, such as in male and female long jump. In those studies, RAE was spotlight among 'All', 'Top25%' and 'Top10%' male long jumpers with a greater effect when the level of competitiveness increased. The authors [88] used polynomial regressions of degree 2 to obtain the rebalancing coefficient. After correction, RAE was no longer spotted among Top25% and Top10% male jumpers. In this study, we chose to run a linear regression by age category to better capture the importance of the relative age effect within each age category. The intention was also to rebalance performances and to observe individually whether this rebalancing allowed potential to emerge. Indeed, the aim was to see the individual impact on performance and not the collective impact on the RAE, hence the rebalancing of all performances and not just the best ones. In addition, validation methods also differ. On one side is checked how much the RAE is reduced by rebalancing the performance. On the other side, the rebalancing method is applied individually to a performance in order to observe how close the rebalanced performance is to the realized one. That is why this method is more revealing of young potentials.

Peak performance is reached earlier in females than in males in these younger categories studying here. This may be related to peak growth velocity. Indeed, studies [244], [245] showed that girls reach their peak growth velocity between the ages of 11 and 13 years, whereas for boys it happens later, between 13 and 15 years. This has an impact on the rebalancing coefficients, which converge more quickly to 0 than for male.

Also, the popularity of an event may have a non negligible impact on RAE [235], especially in popular sports. A concept confirmed by another study, that stated that competition is a fundamental condition for the rise of RAE [156].

We can also wonder if the popularity of an event does, or not, provide the conditions for a recurrence loop, when more media coverage brings more practitioners and higher competitiveness, reinforcing the process of selection. This may explain our non-significant result of skewed distributions of birth quarters in some age categories. RAE is larger in events

where speed and strength are emphasised [103]. In the French Youth Swimming Championships (U11 up to U19) for example, the number of female swimmers participating to the Freestyle 1500m is 25 times lower than in Freestyle 50m [240]. This may explain the link between RAE, competitiveness and popularity.

For all the reasons mentioned above, corrective adjustments should be considered in talent identification and detection programs. Indeed, federations, coaches and staff members should be aware that these methods may reduce biases and dropout rates and increase participation and interest among young talented athletes [104].

Conclusion and perspectives

A relative age effect is present in all types of Track and Field events among both males and females. The level of competitiveness enhances relative age effect. Corrective adjustment methods provide a better objectivation of athletes' performances. Indeed, it is important to make coaches aware of relative age effect. Then, the method we have put in place is designed to be practical for coaches, sport scientists and athletes to apply in the field in order to optimise talent identification and detection programs.

Supporting information

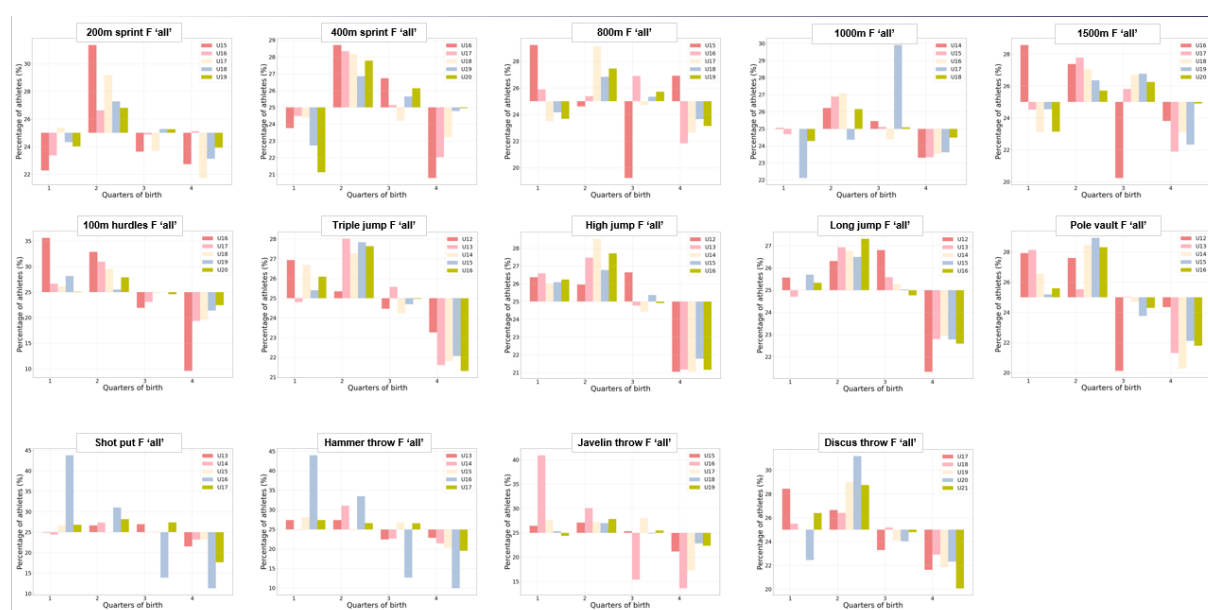


Figure 15: Birth quarters distribution according to age categories for 'all' female events

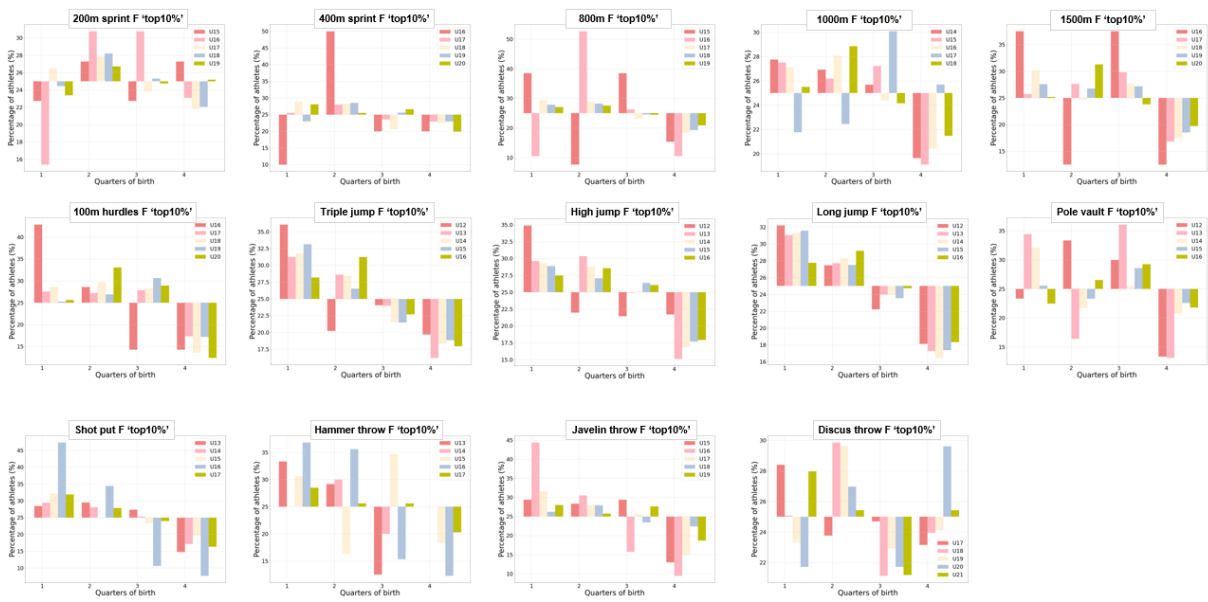


Figure 16: Birth quarters distribution according to age categories for 'Top10%' female events

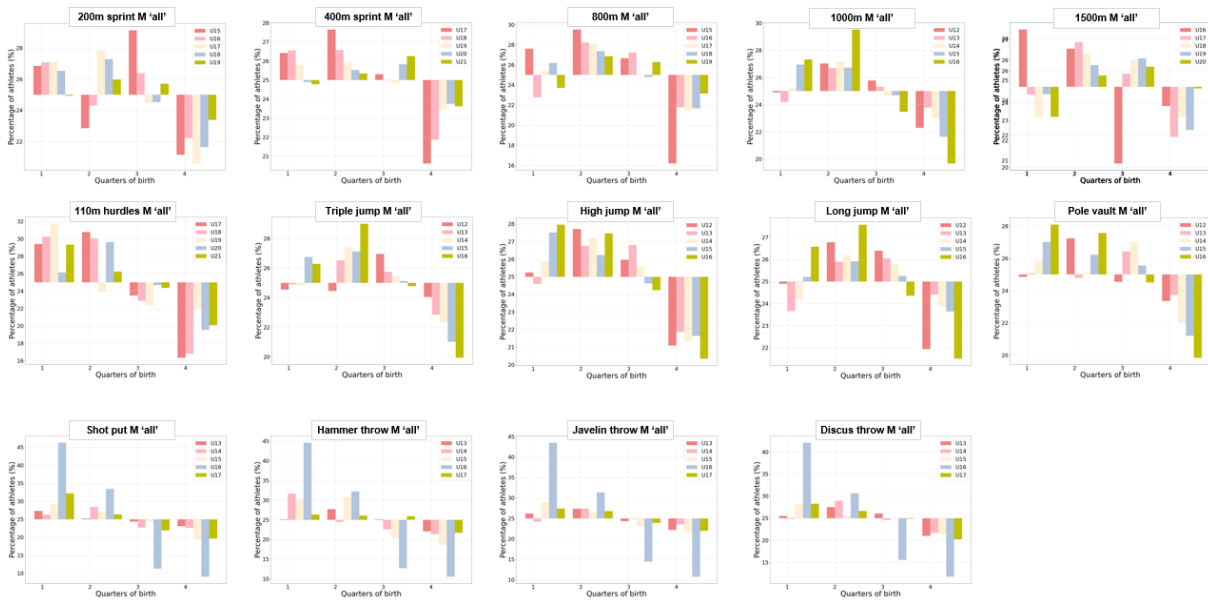


Figure 17: Birth quarters distribution according to age categories for 'all' male events

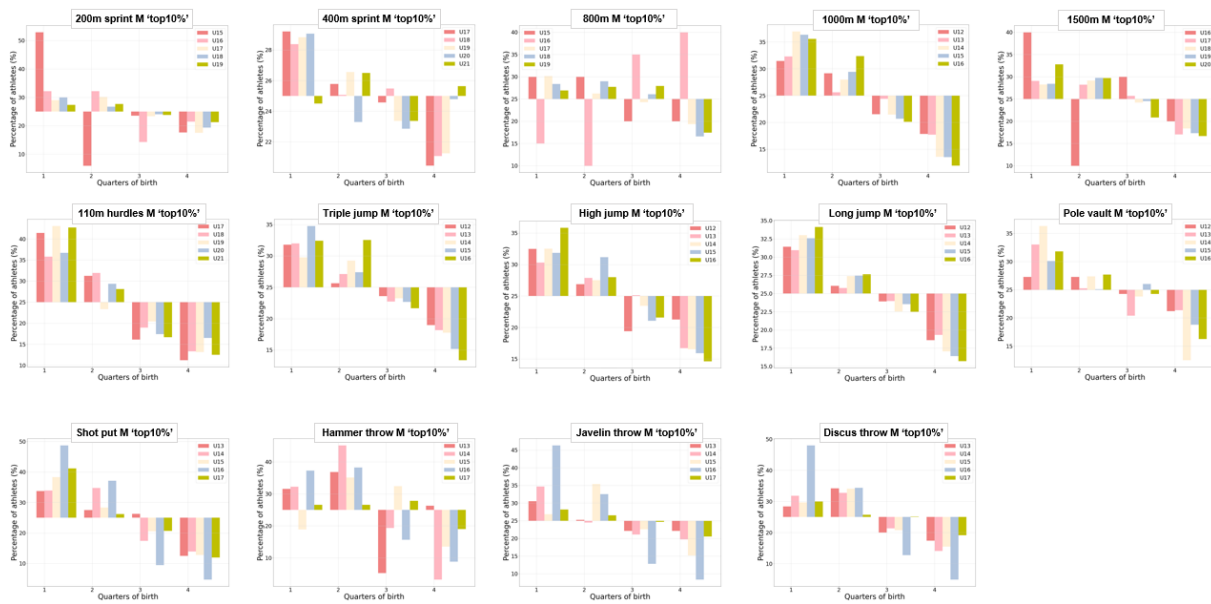


Figure 18: Birth quarters distribution according to age categories for 'Top10%' male events

Panel: Research in context

WHAT WERE THE ISSUES AROUND THIS SUBJECT?

As mentioned above, few studies have applied rebalancing methods to performance, and even fewer estimating potentials. The studies concerned have been aimed at considering relative age.

WHAT DOES THIS STUDY ADD TO EXISTING KNOWLEDGE?

With these rebalancing methods, which work on metric performances, be they times, jumps or throws, we not only erase the relative age effect, but additionally manage to theoretically evaluate all young athletes at the same exact age. This objectivity is the basis for estimating potentials.

TRANSLATIONAL OUTLOOK

One of the consequences of the relative age effect is dropout among youngest (relatively and biologically) athletes. This population feels less observed, receives less attention, is demotivated because they are not yet performing very well, and is gradually pushed towards the exit. One of the reasons for dropout among young female swimmers is lack of success, when they fail to achieve excellent performances [124]. Swimming then becomes less important than other activities.

In this way, study 3 focuses on dropout. More specifically, the aim is to analyze the evolution of dropouts as a function of age, comparing the two sexes and including performance level, as well as the relative age effect on male and female short-distance races.

DROPOUT IN SWIMMING

Study 3

DROPOUT AMONG FRENCH SWIMMERS: GENDER, RELATIVE AGE EFFECT AND PERFORMANCE LEVEL INFLUENCES

Introduction and objective

Dropout is defined as someone who participated in a particular sport and then stopped participating in that same sport but did not permanently stop participating in any other sport [228]. Youth withdrawal may be described as the intentional or mandatory termination of participation in youth sports [123].

Researchers have identified several reasons leading to withdrawal among Finnish athletes [123] or Canadian swimmers [124]: loss of interest, boredom in the current activity, interest in another activity, conflict with the coach, loss of pleasure, frequency of injuries, stagnation of performance or skills. In contrast, athletes who persist in the same sport usually enjoy greater parental support, and the rewards they obtain from their success in competitions create a virtuous circle in favor of commitment [124], though too much pressure from parents during adolescence may also lead to disengagement [125].

Only a few studies have looked at the participation and drop-out rates using KMS (Kaplan Meier Survival) analyses with Cox regression. Between 2008 and 2012, only 17.6% of Flemish gymnasts remained 5 years or more in the high-performance pathway, with an average survival time estimated at 2.5 years [246]. When tested at 7, a similar proportion of gymnasts continued to compete at the highest level at age 12 [246]. In soccer, the relationship between dropout and chronological age were observed in 9908 Canadian girls between 10 and 16 years old [247] : survival analyses show that only 23.3% of the initial population persisted up to the end of the study period, i.e. 7 years [247]. Among female soccer players born during the first quarter of the year, the median survival time was 4 years vs. 3 for those born during the rest of the year [247]. Cox regression showed that birth quarter was not a variable that significantly impacts

dropout rates when level of competition and size of community were included in the analysis [247].

Age, level of competition (district, regional, state or national) and proximity to a large city are associated with increased dropout rates in swimming as opposed to gender and relative age, among 1822 young Australian female and male swimmers (12 - 15 years old) [228]. Although a relative age effect had been shown among young French swimmers, independently from competitiveness and sex [240], no study has investigated dropouts in this population.

Thus, the aim of this study was to investigate the evolution of the dropout rate with respect to sex, level of performance and birth quarters among French male and female Freestyle short-distance (50m) swimmers.

Methods

Data collection

The database from the French Swimming Federation provides all French participation in all types of competitions (local to international) from 2002 to 2020 in all individual events (50m, 100m, 200m, 400m, 800m, 1500m Freestyle, 50m, 100m, 200m Breaststroke, Backstroke and Butterfly). For each swimmer, birthdate, performance time, competition and pool length are available. Only swimmers who started competition before the age of 18 and competed at least two seasons were considered. Swimmers (50.8% females) were divided into age categories. According to the French Swimming Federation, the female age categories are as follows: Kids: under 10 years old, Youth: between 11 and 13 years old, Junior: between 14 and 16 years old, Senior: over 17 years old. For males, the age categories are shifted up by one year. At each age, swimmers are divided into performance decile, according to their best performance. This means that for each age group, in each performance decile, there is the same number of performances and swimmers. Decile 1 consists of the top 10% of performances, while decile 10 is made up of the bottom 10%.

Relative age effect

The distribution of the birth quarters (Q1: January-March, Q2: April-June, Q3: July-September, Q4: October-December) was calculated for each decile. Chi-square tests was run for each age category to identify significant differences of birth quarters between performance deciles.

Dropout

Dropout in this section will be defined as a swimmer disappearing from the database before the age of 21 (as we look at youth dropout) or as the absence for at least two seasons of swimmers not yet 21 years old at the last recorded competition. The starting age is considered at the first time the swimmer appears chronologically in the database, i.e. the age at the first competition. We measure the dropout proportion for each performance decile, event and sex. The dropout rate "r" at age "t" will be expressed as a function of the membership of performance decile D at age t-1. At each age, we perform a linear regression between the dropout rate and decile:

$$r = a * D + b$$

We perform a Student test to test the hypothesis that the coefficient "a", representing the additional percentage per decile, is different from 0 at threshold 0.05.

Survival analysis

To study the evolution of the onset of dropout according to sex and birth quarter, KMS curves were estimated. This method was particularly adapted here as it allows to deal with swimmers who started swimming at different times in their life, considering starting age. In this study, KMS curves were plotted according to relative age in order to compare athletes at a similar stage of their career. Kaplan Meier estimates were computed to determine differences in terms of dropout between birth quarter for each sex. To assess the significance of the results, log-rank tests were performed for each considered groups. This test checks whether KMS curves are significantly different from each other.

Results

160 861 athletes who started swimming before the age of 18 are included in this study (49.2% male). Among those who are at least 21 years old and have been practicing for at least two seasons, 79.1% of male and 87.2% of female have dropped out of swimming. Regardless of the age at which the performances are carried out, girls drop out the most at 13 and boys at 17. When we look at the ratio of these frequencies to the population of the age concerned, the dropout rate is higher at 17 for both girls and boys.

The distribution of swimmers by birth quarters within each performance decile is shown in **Figure 19** for the 50m Freestyle male and female event in the 50m pool at 13 and 17 years old. Swimmers with at least one performance time at 13 and who are more than 15 years old at the last recorded competition are considered here (similarly for 17 years old swimmers, only those with at least one performance time who are older than 19 are included). By conducting a chi-square significance test on all events, females support a significant effect from birth quarter on performance decile from 13 to 18 years of age (and from 13 to 19 years of age for males, except in breaststroke; p-value < 0.05).

At age 13 in decile 1, 40.3% of female swimmers are born in Q1 vs. 12.4% in Q4 (**Figure 19A**), while 47.3% of males are born in Q1 vs. 8.7% in Q4, (**Figure 19C**). The proportion of Q1 decreases significantly and the proportion of Q4 increases significantly as performance level decreases, from decile 1 to decile 10. In decile 10, 28.1% of female (**Figure 19A**) and 32.3% of male swimmers (**Figure 19C**) were born in Q4 vs. 21.0% and 17.3% born in Q1 respectively.

At age 17, the difference is smaller but still present: 29.6% of females belonging to decile 1 are born in Q1 vs 20.5% in Q4, while 34.0% of males are born in Q1 vs 14.1% in Q4. The birth quarter distribution between Q1 and Q4 for all other events is shown in **Table 7** and **Table 8** in **Supplementary File**.

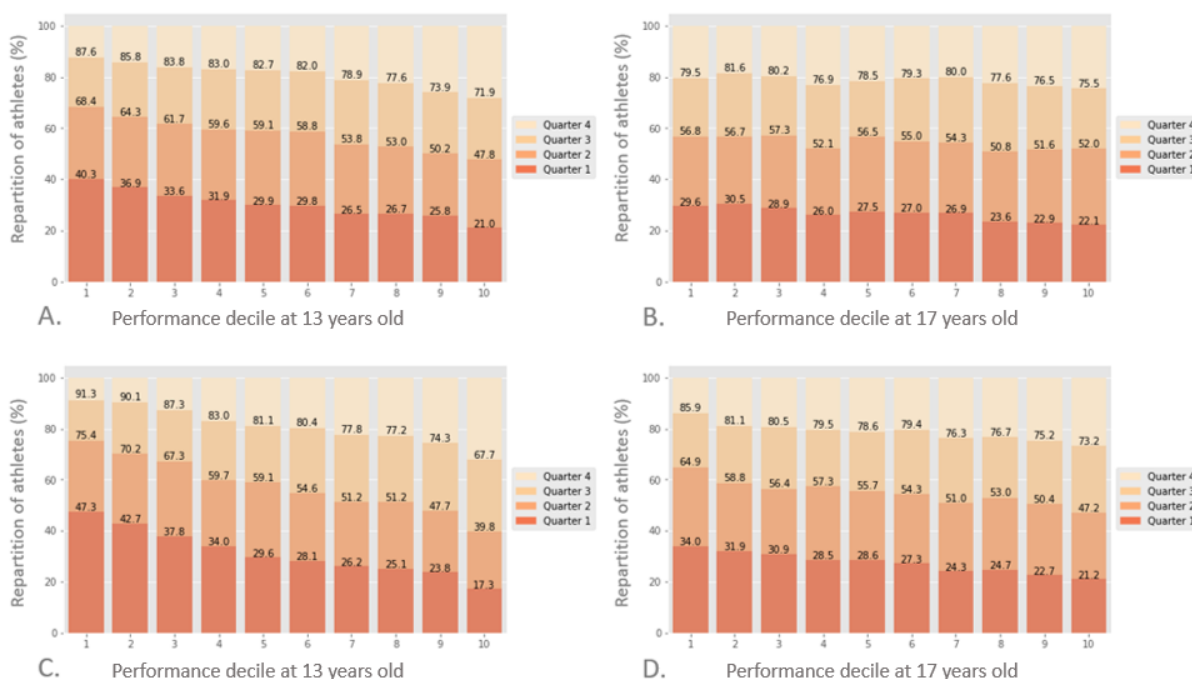


Figure 19: Birth quarter distribution by performance decile

Distribution by birth quarter and performance decile of swimmers at 13 (A) and 17 (B) years old in the female 50m Freestyle competing in the 50m Olympic swimming pools and of swimmers at 13 (C) and 17 (D) years old in the male 50m Freestyle.

The evolution of the dropout rate by performance decile for the female and male 50m Freestyle is presented in **Figure 20**. The dropout rate increases significantly with performance decile. Indeed, for the 14-year-old girls, 8.7% drop out in decile 1 vs. 78.1% in decile 10. Similarly, among 14-year-old boys, a dropout rate of 9.9% was observed in decile 1 vs 69.3% in decile 10. For the 18-year-old swimmers 39.6% of girls and 28.6% of boys in decile 1 drop out the following year, whereas 91.7% of girls and 83.4% of boys from decile 10 did not continue the following year. The dropout rates at ages 14 and 18 according to performance deciles 1 and 10 at ages 13 and 17 respectively are presented in **Table 8 in Supplementary File**.

There is a performance decile effect at age t on dropout at $t+1$. Each additional decile at ages 13 and 17 is associated with an average increase of 7.19% (p-value<0.01) and 5.17% (p-value<0.01) for girls and 6.44% (p-value<0.01) and 5.39% (p-value<0.01) for boys, respectively.

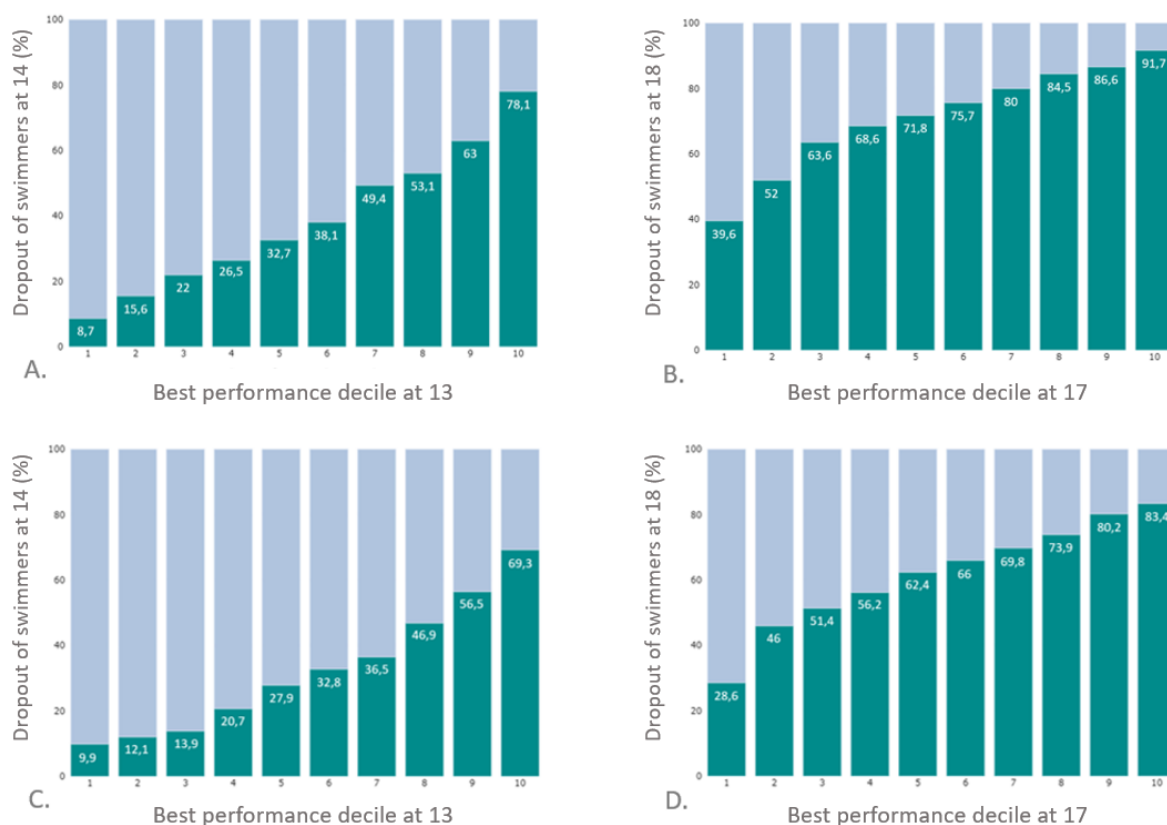


Figure 20: Dropout rates by performance decile

Dropout rate at age 14 based on performance deciles at age 13 in the female (A) and male (C) 50m Freestyle in the 50m Olympic swimming pool. Dropout rate at age 18 based on performance deciles at age 17 in the female (B) and male (D) 50m Freestyle in the Olympic swimming pool (50m).

The KMS curves according to gender are presented in **Figure 21**. 74,922 males and 80,170 females started swimming at 8 years or later. The KMS curves are similar before the age of 14; then, the difference between the two curves becomes significant from the age of 15 onwards (log-rank test: p-value < 0.005): females drop out significantly more than males. The greatest difference between both sexes occurs at 17.89 years, where females are 4.8% more likely to drop out than males.

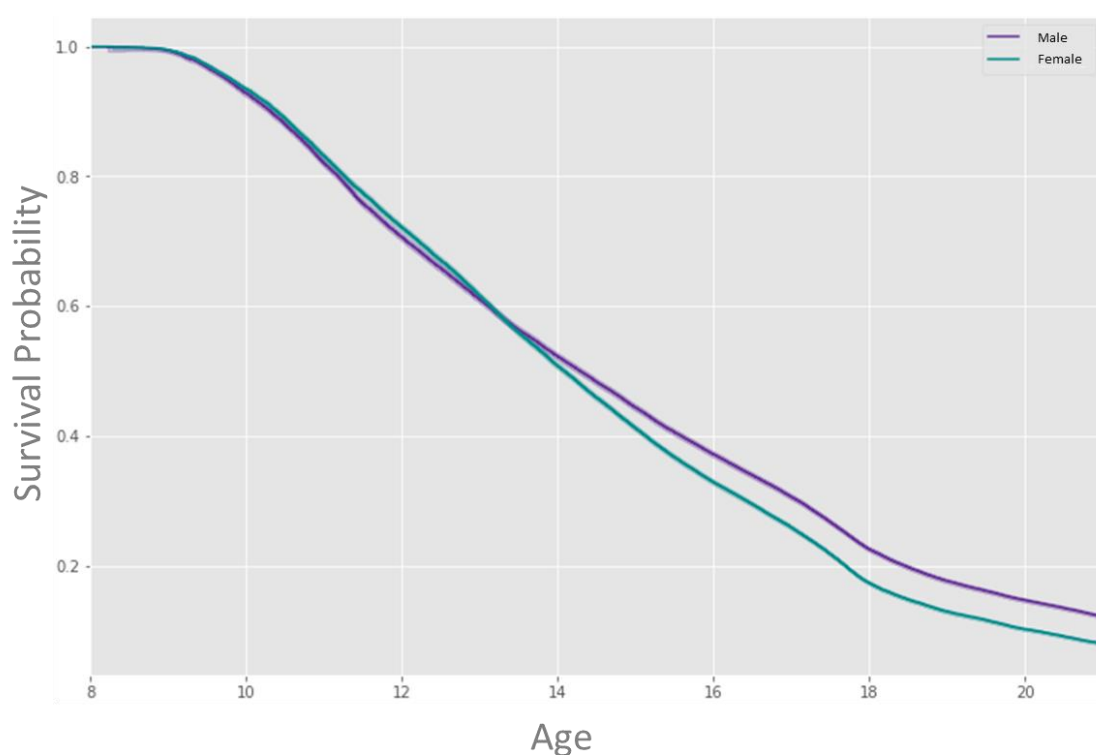


Figure 21: KMS curves by sex

KMS curves by birth quarter are shown in **Figure 22** for both sexes. For females, the KMS curve for quarter 1 is always above that of the other quarters from age 10 onwards, while the KMS curve for quarter 4 is always below that of the other quarters. (log-rank test: p-value < 0.005, **Figure 22C**). Focusing only on the difference between these two quarters, the largest observed difference between the two corresponding KMS curves occurs at 12.71 years old with a 10% difference (**Figure 22D**). For males, the trend is similar with the KMS curve of the first quarter

being above the others and the one of the last quarters being below the others from age 13 onwards (log-rank test: p -value < 0.005 , **Figure 22A**). In addition, at 14.67 years old, age at which the maximum difference is reached, male born in the fourth quarter are 8.1% more likely to drop out than those born in the first quarter (**Figure 22B**).

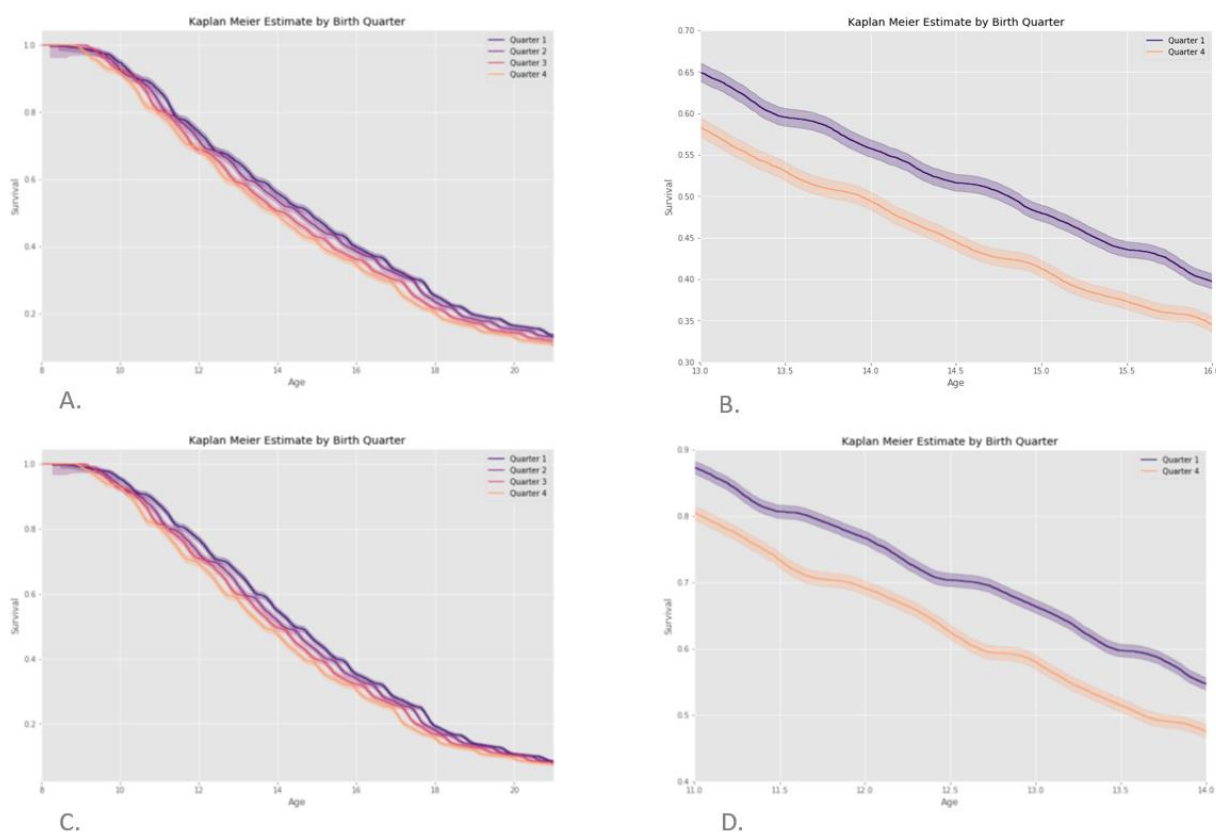


Figure 22: KMS curves according to birth quarters

(A) KMS curves according to birth quarters for males (B) Zoom in on the first and last quarter KMS for males between 13 and 16 years of age (C) KMS curves according to birth quarters for females (D) Zoom in on the first and last quarter KMS for males between 11 and 14 years of age

Discussion

This study highlights the impact of sex, birth quarter and performance level on dropout rates for all swimming events among 8 to 21 years old swimmers. It shows that the dropout rate increases when the level of performance decreases. The Kaplan Meier survival curves show a similar evolution of dropout rates for girls and boys until the age of 13, after which girls tend to drop out significantly more than boys, who face a peak in dropout around the age of 17.

Dropout and birth quarter

A relative age effect is found within the performance deciles, particularly at age 13, for both girls and boys, in accordance with previous study [240]. In the top performance decile, the proportion of swimmers born in the first quarter of the year is consistently higher than the proportion born in the last quarter [8]. Taking the top 10% of a sample of Australian swimmers (equivalent to our performance decile 1), at ages 13, 14, 15 and 16, the proportion born in Q1 is 56%, 42.9%, 50% and 36.4%, while that born in Q4 is 4%, 8.9%, 8.3% and 14.5% respectively. At 13, 14 and 15, the authors identify a large effect size and a medium one at 16 years of age. Difernand et al. [240] also highlight a relative age effect accentuated by the level of performance in French 50m Freestyle swimmers. In a study [104], reveal a similar trend in 12-15-year-old 100m and 200m breaststrokes, with more Q1 born swimmers in the top 10% than Q4.

Yet, month of birth is not the only birth-related variable that affects dropout. The place of birth also seems to have an influence [248]. Brazilian footballers, who were born in the first half of the year in a city with less than 100,000 inhabitants and a human development index (dimensionless composite index between 0 and 1, calculated on the basis of the quality of life of their citizens: health, education, standard of living) above 0.501 are more likely to play in the top teams of the Brazilian football league [248]. Good access to health and education facilities may encourage sports participation, especially among young people [248], and human development index may favor the development of sport [249].

Dropout and performance

We find that the dropout rate is lower when performance level increases. It may be due to the coaches paying more attention to the best swimmers of the category, in the quest of future medals. The relationship with the coach and manager and the attention given to young athletes is a determining factor in future success [250]. To our knowledge, there is no study yet that has quantified dropout by distinguishing performance levels. However, Rottensteiner [123] and Eystein mentioned stagnation or decline in performance as a major cause of low self-esteem, lack of motivation and dropout [251]. Attempting to achieve a higher performance may turn into an obsession and eventually becomes a source of demotivation [251]. Lack of success is one of the major factors for withdrawal from sport [124]. In addition, the desire to spend more

time with friends or practice other activities, with time spent away from sport or school is important [123], [251], [252]. In particular, some “dropped-out” swimmers considered competitive swimming as less important than other activities [124], with a high level of burnout within competitive swimming [253]. When the return on investment is not as good as hoped for, and the results not as expected, the heavy volume of training and the relationship with the coach tend to be blamed [254]. Indeed, swimmers find training intolerable when they are not satisfied with the results.

Dropout age and sex

Our sample of females swimmers present a dropout rate significantly higher than their males' counterparts (87.2% vs 79.8%), in accordance with previous studies [255]. Among the population of French swimmers, females drop out the most at 13 years of age and males at 17, a trend similar to young French footballers [18],[226]. This highest probability of dropping out of swimming at age 13 for girls is consistent with the difference in the two survival curves between the first and last quarters, which peaks at 12.71 years. Erlandson et al. [256] investigated growth and maturation in gymnastics, swimming and tennis among 222 athletes, and suggested that puberty could be an explanatory factor. With the menarche, the body changes which may affect negatively the motivation and slow down the sport practice, with the acceptance of a new morphology, the management of menstruations, the appearance of body hair while going to the pool or the difficulty to fit in a swimming suit.

For boys, on the other hand, the maximum dropout difference between the first quarter and the last quarter occurs at 14.61 years of age, almost two years later than for girls. Once again, the connexion with the onset of puberty may be questioned. Peak of Height Velocity (PHV), *i.e.* the time of maximum height growth, generally occurs later in boys (between 13 and 15 years) than in girls (between 11 and 13 years) [244],[245]. Also, the fact that the probability of boys dropping out is highest at 17 may be linked to the moment of moving out from high school and therefore to a choice to be made. A study [257] of 169 student athletes in team sports (basketball, baseball, softball, volleyball) and individual sports (tennis, golf, cross country, swimming) revealed that more than half of the students report that it is difficult to match both athletic and academic expectations and that it is not easy to find enough time to study during their sport season.

To our knowledge, the only study using Kaplan Meier survival curves to investigate the dropout of swimmers was conducted [228]. Among 7,895 female and 6,545 male swimmers, they found that 33% and 35% respectively dropped out after two years, while the median time of participation before dropout was four years. In contrast, a sample of 10% had been involved in competitions and of the 758 female and 603 male, 28% and 35% respectively dropped out of swimming after two years. The authors revealed that dropout was not associated with sex and birth quarter, unlike in our study. Indeed, by the age of 21, we show that females have significantly dropped out more than males. Other variables are included in the Moulds et al. study, such as socio-economic categories of the swimmer's living area, age category, level of competition, and proximity to a major city. These variables, which are related to the social developmental environment of the young swimmer, are found to be significantly more important and are the strength of this study. Møllerløkken et al [255], in a meta-analysis showed that girls tend to have a higher dropout rate (26.8%) than boys (21.4%). Vilhjalmsón et al. [258] analyzed the sports habits of more than 3000 Icelandic 6th, 8th and 10th grade students. They also found a higher dropout rate for girls at 34% and for boys at 29%. Their study showed that girls are less likely to join a sports club and are less physically active. In this study, girls reported practicing physical activity with their mothers or older sisters, while boys preferred practicing sport with their friends.

Strengths & limitations

In swimming, some strokes require a high level of technique and a longer learning time. Swimming a 50m freestyle is different from swimming a 1500m freestyle at 13 years old. Also, the return on investment may be delayed on longer distances, which may explain a higher dropout rate with the event distance. Experience was not taken into account in this study: some swimmers may regularly compete when others compete only once a year, but this may also be linked to the performance level. Other variables, such as information related to the club, training, school or familial environment, may also be relevant and generate future research.

Conclusion and practical applications

This study highlights the different impacts of sex and performance level on the dropout rate of young French swimmers. Girls drop out more frequently and earlier than boys while dropouts

increase when performance level decreases. In that sense, these results give insights to federations and recall the need to find solutions in order to maintain to keep young people involved in sport activities.

Supporting information

Event	13 years old				17 years old			
	L1		L10		L1		L10	
	Q1	Q4	Q1	Q4	Q1	Q4	Q1	Q4
50m Freestyle - male	47,22	8,78	18,43	31,53	34,01	13,99	20,96	26,74
50m Freestyle - female	46,31	9,28	20,37	28,49	33,69	14,59	21,99	26,70
100m Freestyle - male	44,47	8,58	22,57	27,99	33,01	14,09	22,13	25,86
100m Freestyle - female	41,90	10,22	25,81	22,82	30,92	17,98	23,25	25,22
200m Freestyle - male	42,86	15,87	19,05	33,33	27,56	19,87	16,67	25,64
200m Freestyle - female	46,48	11,27	30,99	26,76	26,88	22,50	22,50	27,50
400m Freestyle - male	43,26	10,69	20,31	28,48	33,92	15,88	19,45	25,54
400m Freestyle - female	43,35	10,12	22,00	28,36	30,56	16,67	21,00	30,30
800m Freestyle - male	40,78	11,73	24,02	25,14	26,69	20,61	23,65	23,31
800m Freestyle - female	48,61	6,62	22,86	26,74	34,12	18,34	22,01	25,00
1500m Freestyle - male	46,96	7,60	18,26	30,75	33,33	17,87	24,15	23,91
1500m Freestyle - female	43,83	7,41	27,16	28,40	34,80	16,00	24,50	24,50
50m Backstroke - male	45,87	7,62	21,63	27,99	31,73	13,92	20,94	25,91
50m Backstroke - female	44,20	9,39	21,40	28,60	33,93	14,60	22,97	25,74
100m Backstroke - male	42,50	13,75	18,75	20,00	31,34	15,42	24,88	19,40
100m Backstroke - female	40,30	12,46	20,78	28,18	29,57	20,43	22,27	23,65
200m Backstroke - male	40,44	12,73	21,85	26,38	29,35	20,46	23,39	24,60
200m Backstroke - female	36,99	13,81	25,49	25,49	27,32	21,43	20,04	25,76
50m Breaststroke - male	37,15	13,14	24,49	25,28	27,62	18,78	19,89	24,03
50m Breaststroke - female	39,24	10,76	26,58	22,15	32,00	17,71	20,00	22,86
100m Breaststroke - male	26,32	10,53	44,44	16,67	32,20	16,95	32,20	15,25
100m Breaststroke - female	39,69	12,02	21,82	28,18	33,11	23,27	21,35	28,31
200m Breaststroke - male	40,05	11,57	25,75	27,26	29,28	22,33	22,83	27,54
200m Breaststroke - female	40,63	11,72	28,63	21,96	27,60	20,00	16,80	24,40
50m Butterfly - male	39,81	12,31	21,55	28,03	35,93	16,71	22,56	24,79
50m Butterfly - female	36,79	12,57	23,01	27,28	37,99	13,98	24,32	22,80
100m Butterfly - male	41,00	13,79	21,46	20,69	35,27	13,53	18,54	28,78
100m Butterfly - female	39,72	12,74	23,05	25,22	30,13	19,24	25,45	25,82
200m Butterfly - male	40,29	15,76	23,76	23,76	27,91	22,09	20,99	25,00
200m Butterfly - female	34,34	24,24	27,27	24,24	27,20	16,00	26,61	17,74

Table 7: Birth quarter distributions for the first quarter (Q1) and the last quarter (Q4) of the year considering performance deciles 1 (L1) and 10 (L10) at 13 and 17 years old for all swimming events

Event	Age	L1 (%)	L10 (%)	Age	L1 (%)	L10 (%)
50m Freestyle - male	13	9,9	69,3	17	28,6	83,4
50m Freestyle - female	13	8,7	78,1	17	39,6	91,7
100m Freestyle - male	13	6,6	71,7	17	27,2	84,7
100m Freestyle - female	13	9,3	78,8	17	38,3	91
200m Freestyle - male	13	5,8	68,6	17	28,2	91,6
200m Freestyle - female	13	6,7	80,5	17	41,4	93
400m Freestyle - male	13	13,1	81,2	17	30,7	91,4
400m Freestyle - female	13	14,4	85,2	17	43,1	96,9
800m Freestyle - male	13	23,8	88,9	17	37,8	95,8
800m Freestyle - female	13	10	78,5	17	48,6	97,1
1500m Freestyle - male	13	17,6	81,8	17	37,9	93,9
1500m Freestyle - female	13	50	100	17	43,8	100
50m Backstroke - male	13	14,4	84,2	17	32,9	90,1
50m Backstroke - female	13	16,2	86,5	17	41,5	93,4
100m Backstroke - male	13	11,4	80,5	17	29,2	92,4
100m Backstroke - female	13	9	84,3	17	38,4	95,4
200m Backstroke - male	13	6	77,9	17	28	93,3
200m Backstroke - female	13	2,9	78,2	17	38,6	95,6
50m Breaststroke - male	13	19,6	84,7	17	34,8	92,1
50m Breaststroke - female	13	20,6	89,2	17	47,2	92,7
100m Breaststroke - male	13	14,7	88,9	17	28,6	92,4
100m Breaststroke - female	13	13	88,5	17	36	94,1
200m Breaststroke - male	13	13,6	84,1	17	26,6	92,9
200m Breaststroke - female	13	12,2	86,8	17	32,9	94,9
50m Butterfly - male	13	7,8	75,7	17	31,2	85,9
50m Butterfly - female	13	7,9	79	17	38,8	91,9
100m Butterfly - male	13	4	73,2	17	28,6	88,5
100m Butterfly - female	13	10,6	88,6	17	34,9	91,2
200m Butterfly - male	13	7,4	73	17	24,5	89,9
200m Butterfly - female	13	0	29,6	17	37	95

Table 8: Dropout rates at age 14 according to performance deciles 1 (L1) and 10 (L10) at 13 years old and at age 18 according to performance deciles 1 and 10 at 17 years old

Panel: Research in context

WHAT WERE THE ISSUES AROUND THIS SUBJECT?

Many young athletes drop out of sport, or swimming in particular, for a variety of reasons: lack of performance, declining motivation, interest in other activities, burnout, stress, etc.

WHAT DOES THIS STUDY ADD TO EXISTING KNOWLEDGE?

The role of sex, birth quarter and performance in dropout among young French swimmers is notable. Indeed, dropout peaks do not occur at the same age depending on the sex, with more girls dropping out around 13-14. The lack of good performances can be a factor of demotivation and subsequently lead to dropouts among swimmers. Additionally, when considering relative age through birth quarters, those born at the end of the year drop out significantly more often than those born at the beginning of the year.

TRANSLATIONAL OUTLOOK

Previous studies have indicated that girls experience greater stress related to their social lives [124], their commitment to higher education, limited engagement in other extracurricular activities, and their body image concerns [259]. Concerning the latter aspect, it is well-established that the body undergoes substantial changes during growth, with girls typically experiencing increases in both fat and muscle mass, while boys tend to primarily gain muscle mass [260]. Moreover, there is a disparity between boys and girls in terms of the timing of peak height and peak weight growth [162]. The age of peak of height velocity (PHV) associated with peak height growth is two years earlier in girls [162]. In contrast, peak weight gain aligns with PHV for girls, whereas for boys, it occurs one to two years later [162]. It is important to acknowledge that the maturation process differs between genders, yet its implications for sports performance are still not well understood. This is the direction in which the objective of study 4 is structured.

MATURITY IN SWIMMING

Study 4

BIOLOGICAL MATURITY AND PERFORMANCE IN YOUTH SWIMMING

Introduction and objective

Numerous studies have linked physical testing to physical maturation, particularly in team sports. One study looked at the impact of maturation and the relative age effect (RAE) across birth quarters on the physical characteristics and abilities on 162 Italian U12 to U15 footballers from elite and non-elite teams [17]. The authors showed that there was no maturation-related difference between the two levels of competition [17]. However, they found that the impact of maturity level was greater than RAE on anthropometric data and motor tests, with a stronger effect at U12 and U14 [17]. In another study involving 34 Portuguese U15 basketball players, the authors set out to determine selection variables for the U16 national team and assess the influence of biological age on players' physical and tactical dimensions [261]. Post-pubertal basketball players score higher on sprint and jump tests in terms of power and blocks [261]. On the other hand, prepubertal basketball players score higher on high-intensity actions [261]. Gryko et al. set up a similar analysis in Polish women basketball players [262]. Despite higher vertical jump values in the more mature women, most of the differences in the results obtained by the women basketball players were not explained by physical tests and anthropometric data [262]. Other studies investigate the impact of maturation on physical tests or anthropometric characteristics [66], [263], [264].

However, age categories are organized according to year of birth, so maturation is not fully considered. What is problematic, as suggested by Cobley et al., is the maturation-selection hypothesis, whereby older players in an age category are more likely to be selected for major competitions thanks to the advantages associated with their relative and biological age difference from younger players. That is why, in this study, we aim to relate maturation to the performance of male and female swimmers during their races at the French Junior Championships.

We assume that we will find a selection bias towards swimmers who are born earlier and who are in an advanced maturity status in higher level swimmers than their lower-level peers.

Methods

Data collection

The data was collected during the French Junior swimming Championships held in May 2022. The events included in the competition are 50m, 100m, 200m, 400m, 800m, 1500m Freestyle, 50m, 100m, 200m Breaststroke, Backstroke and Butterfly. For each swimmer, mass, seated height, standing height, performance, event, date of birth and sex were collected. In addition, the performances achieved before this competition in the events concerned were provided by the French Swimming Federation. The swimmers are categorized into performance deciles, which are based on their best performances achieved at different ages. This categorization ensures that each age group and performance decile contain an equal number of performances. Decile 1 consists of the top 10% of performances, representing the best achievements, while decile 10 represents the bottom 10% of performances, the less competitive results. This ensures that within each age group and performance decile, an equal number of performances and swimmers are represented. We will compare the number of events in which swimmers are entered based on their performance decile to observe if there is a significant relationship between these variables. The first goal is to determine if swimmers from decile 1 significantly participate in more events than their counterparts from decile 10. For this, a Wilcoxon test is conducted to determine if this is the case significantly.

Maturation

The maturity offset is the time between chronological age and age at Peak at Height Velocity (PHV). It is obtained using the Mirwald equation [7], with one for each sex based on mass, sitting height, standing height and chronological age. Once we have estimated the level of maturity, we put it into perspective with performance broken down into deciles. A contingency table will be used to identify where swimmers are distributed based on their maturation. If a swimmer achieves n performances, he will appear n times. The second objective is to observe if the most mature swimmers are significantly more prevalent within the highest-performing deciles. To

assess this, we utilize a Wilcoxon test to establish whether there exists a significant difference in the proportion of mature swimmers between the first and tenth decile.

Results

247 male and 235 female swimmers were included in this study, as presented in **Table 9**. They achieved 983 and 970 performances in a total of 28 events over 6 days.

	Females Juniors Swimmers			Male Junior Swimmers		
	<i>Mean ± std</i>	<i>Min</i>	<i>Max</i>	<i>Mean ± std</i>	<i>Min</i>	<i>Max</i>
Age	15.13 ± 1.06	13.45	17.41	16.4 ± 1.07	14.43	18.36
Height	167.48 ± 6.03	150	187	180.61 ± 6.41	163	202
Sitting Height	87.80 ± 3.94	58.5	97.3	93.31 ± 3.67	82	105
Mass	56.64 ± 6.88	35.7	76.7	67.4 ± 7.08	45.6	88.6
FATM	11.10 ± 3.38	1.5	21.5	7.66 ± 2.90	1.6	16.5
PMM	43.22 ± 5.63	26.8	67.7	56.74 ± 6.30	37.7	81.7
FFM	45.53 ± 5.92	28.3	71.3	59.74 ± 6.60	39.8	85.9

Table 9: Descriptive statistics of participants in the 2022 French Junior Championships

FATM: body fat mass (kg), MM: muscle mass (kg), LM: lean mass (kg)

The maturity offset of female swimmers who took part in the French Junior Championships is shown in **Figure 23** and that of male swimmers in **Figure 24**. All female swimmers have reached their peak. Only 3 passed their peak less than a year ago. Among male swimmers, 15 passed their peak less than a year ago, although all of them also passed their peak.

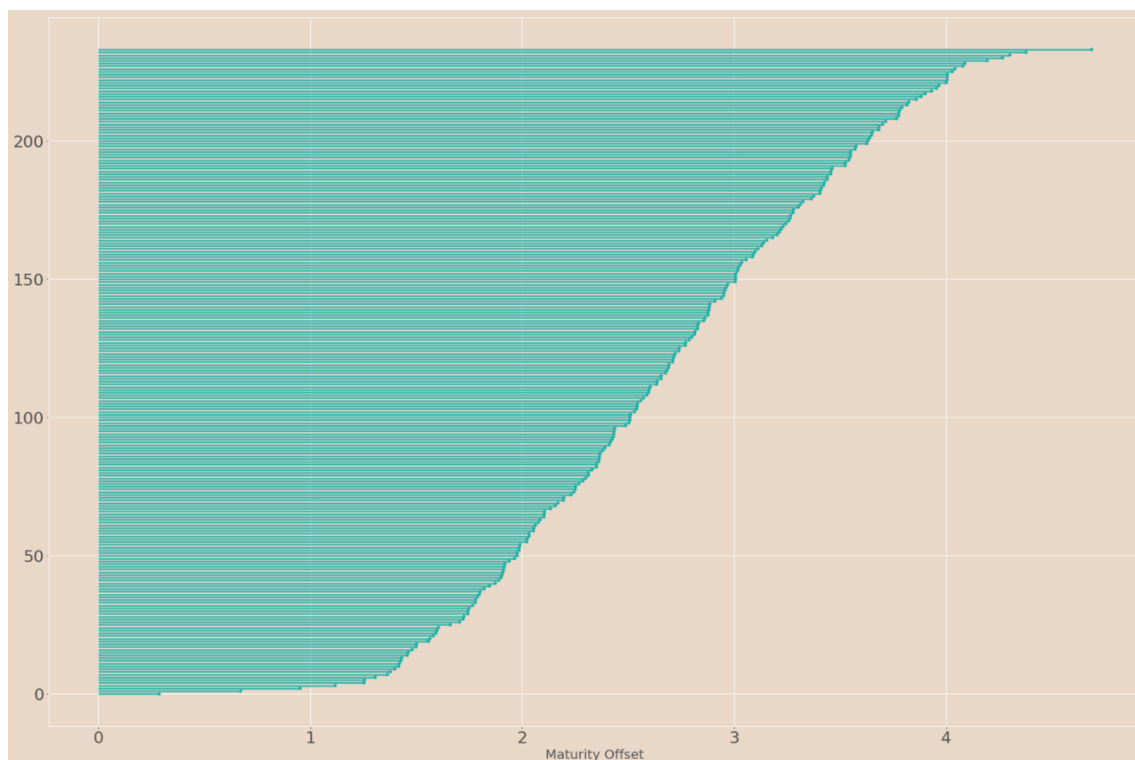


Figure 23: Distribution of female swimmers in the 2022 French Junior Championships according to their maturity offset

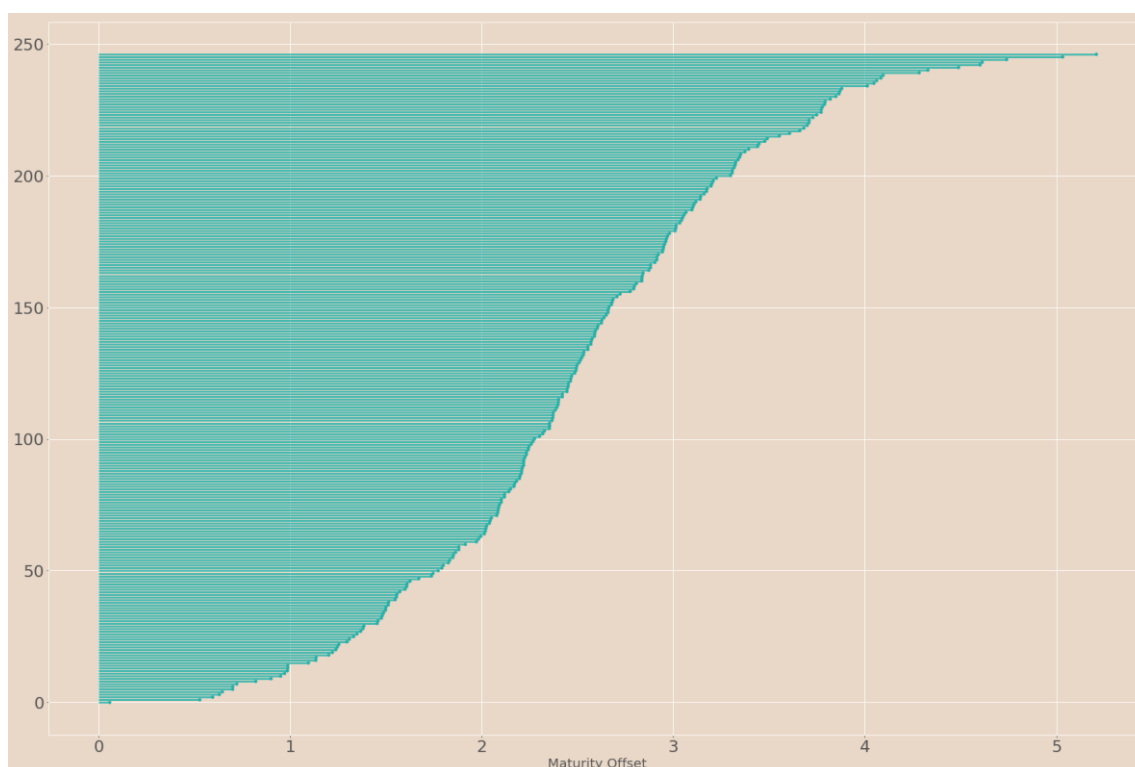


Figure 24: Distribution of male swimmers in the 2022 French Junior Championships according to their maturity offset

The number of events completed by type of performance decile is shown in **Figure 25** for female swimmers and **Figure 26** for male swimmers. There is a tendency to swim more events when the athlete is in a better performance decile. Female swimmers in the first decile participate in significantly more events than those in the tenth decile (first decile: $4.77 + 1.47$ vs last decile: $2.8 + 1.09$, p -value < 0.01). Male swimmers also in the first decile participate in significantly more events than those in the tenth decile (first decile: $4.33 + 1.07$ vs last decile: $3.33 + 0.5$, p -value < 0.1).

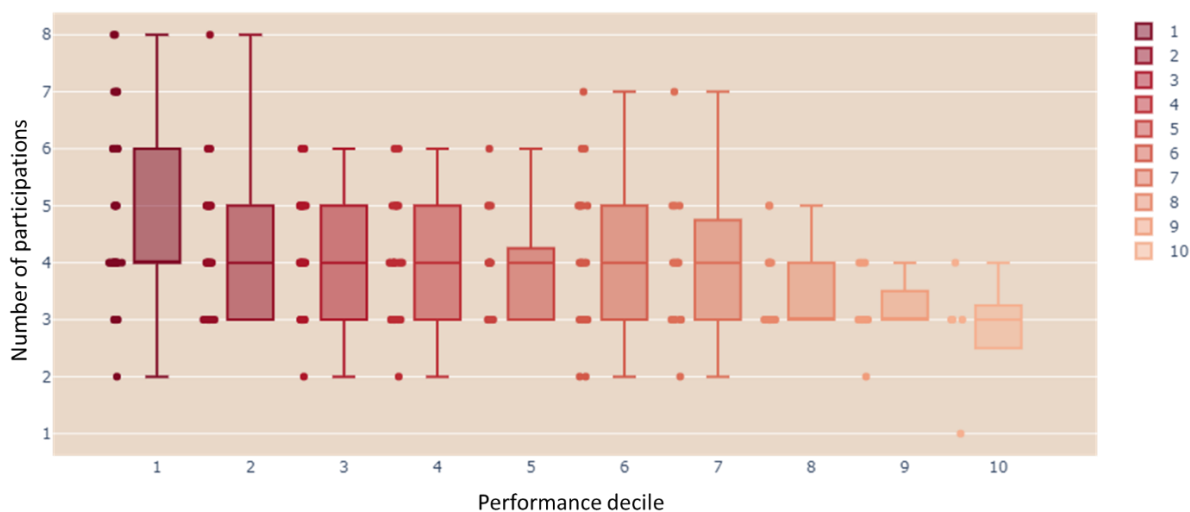


Figure 25: Number of participations in events by performance decile among female swimmers

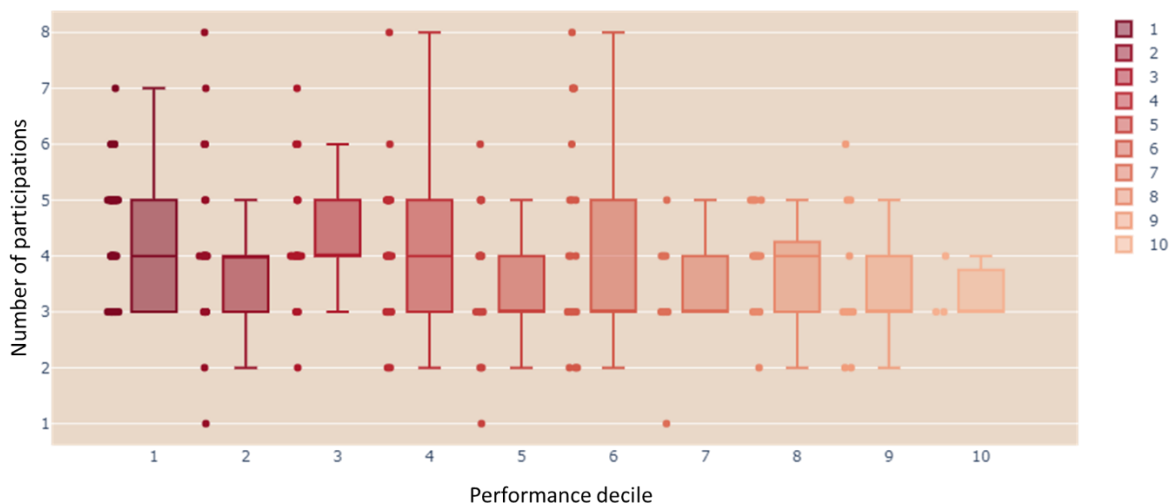


Figure 26: Number of participations in events by performance decile among male swimmers

The link between maturity offset and performance deciles is shown in **Figure 27** for female swimmers and **Figure 28** for male swimmers. For female swimmers, the best performers show

significant higher maturity offset than their lower counterparts (**Figure 27**). Indeed, 87.0% of the first decile female swimmers (38, 25, 17 and 14 swimmers) obtain a maturity offset between 4.69 and 3.28. The lowest female performance swimmers show significant lower maturity offset than their more successful counterparts. Indeed, 86.1% of the tenth decile female swimmers (23, 27, 19 and 18 swimmers) obtain a maturity offset between 2.53 and 1.74.

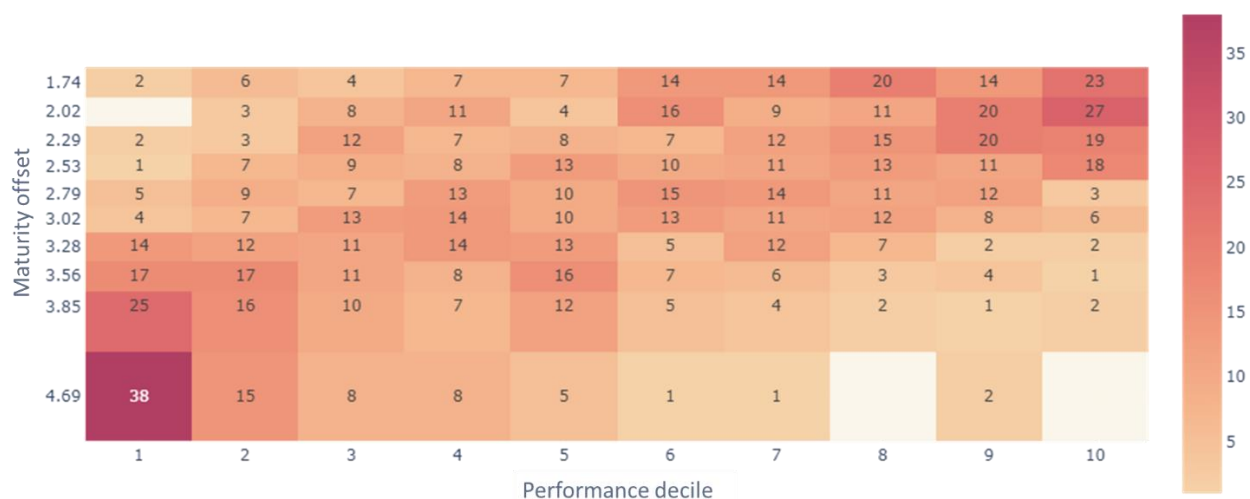


Figure 27: Distribution of female swimmers according to their maturity offset and performance decile

In the case of male swimmers, the top-performing individuals exhibit a significantly higher maturity offset compared to their counterparts with lower performance levels (**Figure 28**). Specifically, 74.5% of the male swimmers in the first decile (36, 23, and 20 swimmers) achieve a maturity offset ranging from 5.21 to 3.3. Conversely, the male swimmers with the lowest performance levels display a notably lower maturity offset compared to their more accomplished counterparts. Similarly, 58.3% of the male swimmers in the ten deciles (34 and 26 swimmers) achieve a maturity offset within the range of 1.35 to 1.79.

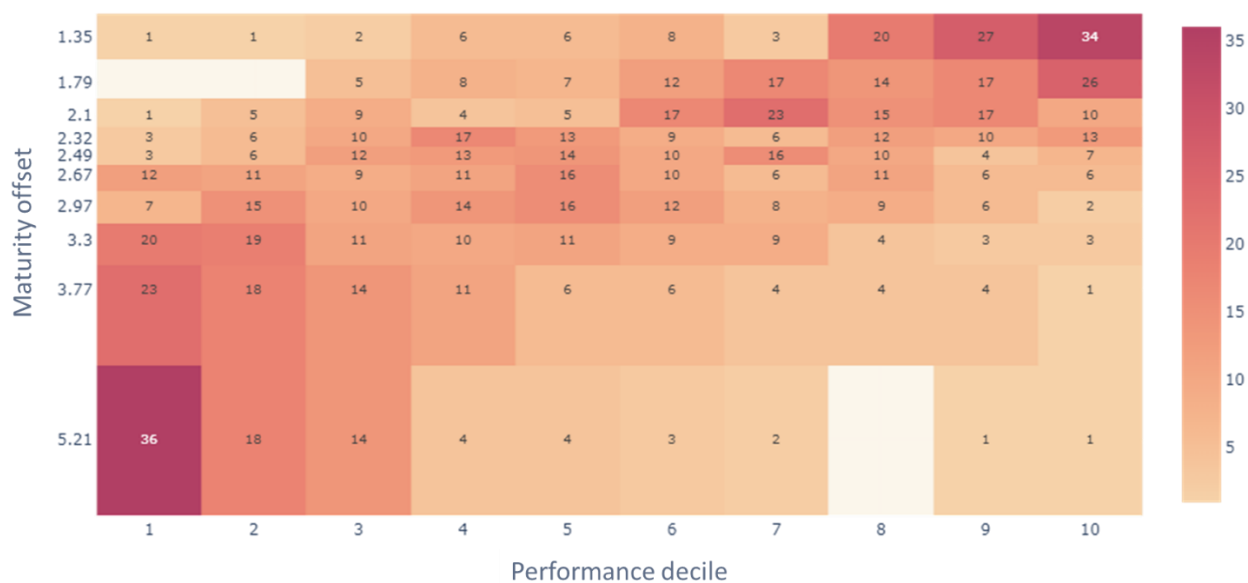


Figure 28: Distribution of male swimmers according to their maturity offset and performance decile

Discussion

The findings from this research reveal that swimmers ranked in the top performance decile participate significantly in a greater number of events at the French Junior Championships compared to their counterparts in the lowest decile. Moreover, the swimmers achieving the highest levels of performance are predominantly those with the greatest maturity offset.

Half of the top-performing swimmers participate in more than four events during this competition. No previous research has investigated the influence of competing in multiple events on performance among French swimmers. However, this serves as a reminder and brings us closer to the concept of performance diversification. Diversification involves engaging an athlete in a range of different sporting activities or events rather than solely specializing in a single sport or discipline [188]. As suggested by Yustres (2021), it is necessary to investigate the role of diversification in achieving high-level performances in senior athletes [265]. To our knowledge, no study to date focusing on able-bodied athletes has examined this issue. However, Schipman et al. have examined the performance of para swimmers between 2009 and 2019 [266]. They observed that when considering all events collectively, it was observed that female Para swimmers achieving higher performance levels were significantly linked with participating in a greater number of race events [266]. This results in a significant performance

difference between those who participate in a single event and those who participate in more than 5 events, except in the individual medley [266]. The same pattern holds true for male Para swimmers as well [266].

When comparing the maturity offset with the performance deciles, we see that those who are most advanced in their maturity are in the majority in the best-performing deciles. In their study observing swimmers aged 8 to 18 swimming backstroke, Alshdokhi et al. analyzed progression rates across different age groups [267]. Throughout the early stages of competitive swimming (ages 8–10), they witness advancements of nearly 10% within a single year [267]. However, as swimmers progress through the middle years (ages 11–14), a more moderate improvement of 5 to 7% becomes a reasonable expectation [267]. As for the later years (ages 15–18), more modest progress is expected, typically ranging between 1–2% [267]. Knowing that the variability in performance levels among adolescent swimmers is influenced by factors as growth and maturation [268]–[270] but not only. Other potential contributors include injury, illness, improper training volumes, as well as enhanced support and training conditions [271]. Marcos et al. investigated the influence of anthropometric variables on performance in the 50m freestyle among junior swimmers [272]. They observed no significant impact of these variables and biological maturation within their study population, suggesting that maturation does not confer an advantage in this event's performance [272]. Similar research leading to the same conclusion was conducted by Nevill et al., where no effects of height, mass, and maturation were demonstrated [273]. However, Pla et al. highlights in the top 100 international male and female swimmers from 50 to 1500m freestyle events for the 2000–2014 seasons, that morphological parameters are associated with performance [231]. Early maturers, which in our study refers to those with the highest maturity offset, could potentially gain more advantages. Due to their relatively greater increases in mass and height compared to those who experience PHV later, they might possess a significant advantage, particularly in sprint events. Additionally, several studies also support the idea that swimming speed increases with height [231], [274], [275]. These considerations align with the maturation-selection hypothesis proposed by Copley, suggesting that those most likely to be selected for participation in national training camps or international competitions could be favored [235].

However, the limited sample size, 85 [272] and 40 swimmers [273], remains insufficient for conducting a statistical analysis that would generate a model highlighting the variables

associated with the personal best (PB) performance. Research findings indicate that studies utilizing allometry for data normalization have not succeeded in identifying significant effects of biological maturation on athletic performance [276]. Additionally, the data in both studies only consider PB, thus lacking longitudinal follow-up that would enable the detection of significant progress or exceptional performance linked to maturity level.

Abbott et al. conducted a similar study with 64 swimmers, incorporating indicators of technical efficiency like the stroke index [277]. It serves as an indirect measure of swimming efficiency [277]. It is obtained by multiplying the swimmer's velocity by the stroke length (measured in meters per cycle), where stroke length represents the horizontal distance covered in a single stroke cycle [277]. This stroke length is calculated by dividing the swimmer's velocity by the stroke frequency [277]. Variations in performance among individuals and stroke index were linked to differences in maturity status [277]. Moreover, they found curvilinear patterns illustrating the longitudinal associations between maturity status and both 200-meter front-crawl velocity and stroke index [277]. They also highlighted that the mean rate of progression rate in stroke index reached its maximum during the years before peak growth phases [277].

In their longitudinal study, Lätt et al. observed 29 male swimmers over two successive years in order to analyze the progression of physical, physiological, and biomechanical variables [270]. They showed that progression in swimming performance around PHV were primarily linked to the growth in body height and arm-span measurements [270]. This provides further evidence for the concept that early maturation enhances speed, possibly because of increased propulsive forces (i.e., thrust) [278] and, thus, performance [279].

Limits

We used the Mirwald equations for computing the maturity offset for each swimmer [165]. Nevertheless, these individuals have already surpassed their peak growth, with most of them doing so over two years ago. As these individuals move further away from their Peak Height Velocity (PHV), the applicability of the Mirwald equations diminishes. Despite this limitation, we opted to employ the Mirwald equations in this study to offer an indication of the swimmers' maturity levels. Conducting more comprehensive research in the younger age category would be intriguing. Individuals in this age range would be closer to their PHV, resulting in more precise estimates of maturity offset. Conversely, considering the substantial dissimilarity

between the population in which Mirwald et al. tested and validated their equations and our specific sample, the estimates may be even less reliable. Our dataset includes mass and sitting height measurements from a cohort of elite male and female athletes who possess distinct morphological attributes compared to Mirwald's study population, which is notably less athletically inclined. Furthermore, in the events, there is not an equal number of swimmers. Some events, such as the 1500m Freestyle, are less commonly practiced and may only have 2 to 3 swimmers in their decile. In contrast, the 50m Freestyle, for instance, is a highly practiced stroke and can feature up to 5 times more swimmers per decile. This leads to the observation that the reasoning on a decile basis differs in relation to the number of competitors participating in the event.

Conclusion and practical applications

This study highlights that the best swimmers compete in more events and are more mature than their fewer fast counterparts. Consequently, performance assessment is impacted by maturity status. These results underscore the importance of considering maturation when evaluating swimmers within specific age groups, for a more comprehensive swimmer support. Further studies are needed, particularly in the younger age category, to be closer to PHV and to ensure more accurate estimates of maturity offset, despite the inherent limitations.

Panel: Research in context

WHAT WERE THE ISSUES AROUND THIS SUBJECT?

Biological age and maturity level are factors that are still relatively underappreciated in the assessment of performance and the selection of young athletes.

WHAT DOES THIS STUDY ADD TO EXISTING KNOWLEDGE?

This initial correlation between maturity offset and performances achieved at the Junior French Championships provides results that support the notion that maturity level influences performances.

For instance, we could conceive four types of associations between maturation and performance, to observe the corresponding types of evolutions (**Figure 29**):

- Weak maturity offset and weak performance (in green),
- Advanced maturity offset and weak performance (in blue),
- Weak maturity offset and good performance (in orange),
- Advanced maturity offset and good performance (in purple).



Figure 29: Distribution of female swimmers according to their maturity offset and performance decile on 50m freestyle

The performance trajectories according to the previous groups are shown in **Figure 29**. Swimmer 1 and swimmer 4 are very close in terms of performance times, with respectively 27.07s at 14.14 years old and 26.33s at 17.18 years old. However, swimmer 1 seems to be

improving compared to her previous performance. Meanwhile, swimmer 4 seems to be constant based on her most recent performances. The other two swimmers performed less well, as we can see on **Figure 30**.

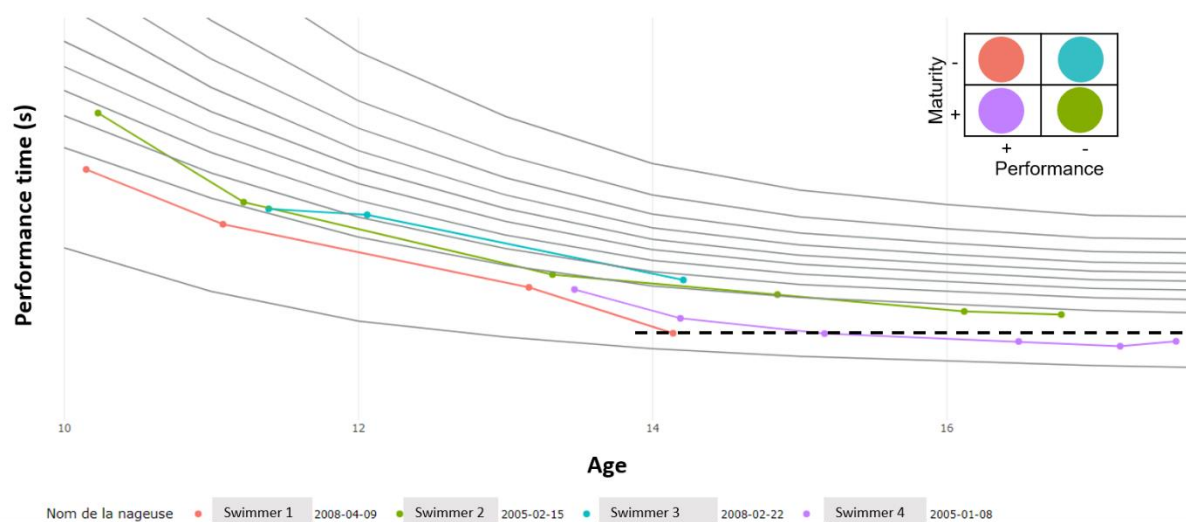


Figure 30: Examples of evolution of performance trajectories of female swimmers from the different maturity-performance associations

(orange: high performance and low maturity offset, purple: high performance and high maturity offset, blue: low performance and low maturity offset, green: low performance and high maturity offset)

TRANSLATIONAL OUTLOOK

Having a longitudinal follow-up of these swimmers is a subject of an interesting study, as done by Abbott et al [277]. Indeed, we can inquire whether swimmers who were relatively less mature during these French Championships firstly continued their practice in this event and secondly, if they also progressed more or achieved better performances than the more mature swimmers, during the Junior French Championships of the following year. To go further, it would be relevant to explore their future sports career in terms of their participation in senior category competitions. This is partially the focus of the upcoming study, which examines the conversion rate from junior to senior levels among French swimmers in major international competitions.

EARLY SPECIALIZATION

Study 5

EARLY SPECIALIZATION IN FRENCH YOUTH SWIMMING

Introduction and objective

The career trajectories of athletes are increasingly becoming a subject of extensive research. [126]. In particular, researchers are focusing on anterior performances trajectories' and the moment when athletes reach the senior category. Various sports have been the target of these investigations: football [127], [128], volleyball [130], judo [130], tennis [135], track-and-field [236], [280], [281], cycling [134], taekwondo [131], wrestling [131] and boxing [131]. Swimming is one of the most studied sports in this context. Yustres et al. investigated the transition rate of British swimmers who participated at the World Championships between 2006 and 2017 [265]. Among the 141 swimmers, 77 swimmers (54.61%) competed in World Championships, and 53 (37.58%) participated in junior World Championships, with only 11 swimmers competing in both categories [265]. As a result, only 17.19% of British junior swimmers went on to participate in senior World Championships later in their careers [265]. Swimmers who reached junior finals had higher chances to be qualified for senior World Championships than those who only made it to junior semi-finals or heats [265]. The same trend is found in Barreiros et al. [130] with higher percentages but a smaller sample size. Among 60 pre-junior male swimmers born between 1974 and 1981, participating in international competitions between 1988 and 2008, 56.7% were selected in juniors and 30% in seniors [130]. Similarly, among their 64 female counterparts, 57.8% were also in juniors and 32.8% in seniors [130]. These findings are supported by Brustio et al. who analyzed the career paths of a total of 6631 European swimmers, with 41.8% of females, who participated in all individual 50m and 100m events [129]. The average transition rate for juniors males was 21%, while for females, it was 25% among the top 50 swimmers for all strokes and junior ages included [129]. When considering the top 100, the transition rate was between 14 and 26% for males and between 23 and 33% for females [129]. The larger the top, the higher the transition rate [129]. However, to our

knowledge, no study has focused on all individual non-combined swimming events and considered the senior, junior, and pre-junior categories, which will be called youth from now on. Therefore, this study aims to investigate the transition rates between the different aforementioned categories, both prospectively and retrospectively, among the top French swimmers.

Methods

Data collection

The database provided by the French Swimming Federation contains all performance times of any French participation in various competitions, ranging from local to international events, spanning the period from 2002 to 2020. These results concern all individual non-medley events, including Freestyle (50m, 100m, 200m, 400m, 800m, and 1500m), Breaststroke (50m, 100m, 200m), Backstroke (50m, 100m, 200m), and Butterfly (50m, 100m, 200m). For each swimmer, the database includes essential information such as their birthdate, gender, performance time, the competitions they participated in, and the length of the pool. The swimmers are categorized into performance deciles, which are based on their best performances achieved at different ages. This categorization ensures that each age group and performance decile contain an equal number of performances. Decile 1 consists of the top 10% of performances, representing the best achievements, while decile 10 represents the bottom 10% of performances, the less competitive results. Swimmers are categorized into different age groups: Youth (13-14 years), Junior (15-18 years), and Senior (over 18 years). Within each age group, only the best performance per event and per swimmer is recorded. The performances are then ranked from best to worst, and only the top 10% are retained, representing the best decile.

Conversion rate

Firstly, we examine whether the swimmers in the first age category are also present in the next age category. We calculate the conversion rates between Youth and Junior, between Junior and Senior, and between Youth and Senior. For instance, the conversion rates from Junior to Senior is calculated with the ratio between the number of swimmers in decile 1 in both Junior and Senior categories and the total number of swimmers in decile 1 among Juniors.

Insertion rate

The insertion rate is defined similarly, representing the proportion of swimmers in decile 1 who originate from decile 1 of the previous age category. This involves the insertion rates between Senior and Junior, Junior and Youth, and Senior and Youth. The calculation is based on the ratio between the number of swimmers in decile 1 for Juniors and Seniors and the total number of swimmers in decile 1 among Seniors.

Conversion-insertion rates in major international competitions

These same conversion and insertion rates will be calculated across different international competitions, both in Junior and Senior categories: European Championships, World Championships, and Olympic Games. Also, a swimmer appears only once in the Junior category and once in the Senior category. The competitions have been ranked in order of prestige: Olympic Games, World Championships, and then European Championships. Thus, we have retained the most prestigious competition in which the swimmer participated.

Statistical analysis

Regarding conversion and insertion rates, z-tests will be conducted for each event, comparing the proportions pairwise to identify if they are significantly different from each other.

Results

A total of 12,786 youth, 10,921 juniors, and 10,717 seniors belonging to decile 1 of the respective categories are presented in **Table 10**.

Categories	Performances		Swimmers	Age	First performance age
	Total	Average (\pm sd)	Total	Average (\pm sd)	Average (\pm sd)
Youth	1 037 858	81,17 (\pm 41,49)	12 786	14,08 (\pm 0,57)	13,20 (\pm 0,35)
Junior	1 228 044	112,45 (\pm 63,85)	10 921	16,39 (\pm 0,84)	13,93 (\pm 1,28)
Senior	909 037	84,82 (\pm 101,98)	10 717	23,11 (\pm 6,2)	17,76 (\pm 5,95)

Table 10: Description of the population of decile 1

The conversion rates between different categories are presented in Table 2. The z-tests indicate that the proportions of youth-seniors conversion rates ($22,71 \pm 4,50$ %) vs juniors-seniors conversion rates ($40,2 \pm 6,46$ %) are significantly different, as well as youth-juniors conversion rates ($51,29 \pm 3,73$ %) vs youth-seniors conversion rates in all events. Between youth and juniors, the lowest conversions rates mainly concern long-distance or fairly technical events such as breaststroke or butterfly. The significant conversion rates between juniors and seniors is below 50% for the 100m and 200m butterfly events in both males and females. This trend is also evident in the conversion between youth and seniors, despite the 1500m freestyle in the 50m pool for females. On the other hand, when we look at the highest significant conversion rates, similar trends emerge for seniors, with events in the 25m pool and a majority of 50m events, despite a few long-distance events.

Events	From Youth to Juniors (%)	From Juniors to Seniors (%)	From Youth to Seniors (%)
1500m freestyle females (25m)	42,65	22,30	11,76
200m butterfly females (25m)	45,66	24,15	11,62
800m freestyle females (25m)	38,45	24,65	10,21
200m butterfly females (50m)	52,97	27,31	17,82
200m backstroke females (25m)	48,38	29,42	15,30
800m freestyle females (50m)	51,62	29,66	15,68
1500m freestyle females (50m)	46,25	30,56	16,25
100m butterfly females (50m)	54,69	30,86	19,90
400m freestyle females (25m)	47,25	31,03	16,06
200m breaststroke females (25m)	46,39	31,15	16,93
100m butterfly females (25m)	48,38	31,61	16,11
200m backstroke females (50m)	51,79	32,07	17,14
400m freestyle females (50m)	50,86	32,94	17,87
200m freestyle females (50m)	57,14	33,01	19,14
200m freestyle females (25m)	50,64	33,04	17,84
800m freestyle males (25m)	30,92	34,18	11,98
100m backstroke females (50m)	51,68	35,11	20,00
50m butterfly females (25m)	52,92	36,20	20,26
1500m freestyle males (25m)	46,16	36,35	18,60
200m breaststroke females (50m)	51,49	36,39	20,43
200m backstroke males (50m)	57,72	37,25	24,38
100m freestyle females (50m)	57,48	37,48	22,16
200m butterfly males (50m)	54,85	37,50	22,82
100m backstroke females (25m)	49,47	38,61	21,17
200m backstroke males (25m)	51,84	39,59	22,25
50m butterfly females (50m)	57,69	39,66	24,52
100m backstroke males (50m)	58,45	39,95	26,58

100m breaststroke females (25m)	45,07	39,98	19,67
50m backstroke females (25m)	47,34	40,00	21,25
200m butterfly males (25m)	48,02	40,76	22,04
50m backstroke females (50m)	53,09	40,81	24,13
100m freestyle females (25m)	52,14	40,87	22,74
50m breaststroke females (25m)	45,87	40,88	21,11
1500m freestyle males (50m)	49,28	41,23	21,22
100m breaststroke females (50m)	51,81	41,34	21,82
50m freestyle females (50m)	57,03	41,71	24,08
800m freestyle males (50m)	47,87	42,50	24,17
200m breaststroke males (25m)	48,77	42,52	22,89
100m butterfly males (50m)	59,70	43,02	29,34
400m freestyle males (50m)	51,39	43,70	24,25
50m freestyle females (25m)	53,04	44,33	25,94
200m freestyle males (50m)	58,74	45,00	27,37
400m freestyle males (25m)	49,34	45,09	24,40
50m breaststroke females (50m)	49,74	45,59	24,66
200m freestyle males (25m)	53,44	45,65	26,59
100m butterfly males (25m)	51,59	46,25	27,16
100m backstroke males (25m)	50,64	47,51	27,38
200m breaststroke males (50m)	57,10	48,51	28,96
50m backstroke males (25m)	50,12	49,08	26,75
50m backstroke males (50m)	55,61	49,26	31,54
50m breaststroke males (25m)	49,40	49,65	27,18
100m freestyle males (50m)	58,48	49,68	30,07
50m breaststroke males (50m)	52,17	49,69	29,57
100m breaststroke males (50m)	55,52	50,20	29,89
100m breaststroke males (25m)	48,68	50,52	26,67
50m butterfly males (25m)	54,82	50,74	30,36
50m freestyle males (50m)	55,58	51,59	30,28
50m butterfly males (50m)	57,11	52,15	30,63
100m freestyle males (25m)	53,08	53,47	30,58
50m freestyle males (25m)	51,79	56,74	33,04
Mean (\pm std)	51,29 (\pm 3,73)	40,2 (\pm 6,46)	22,71 (4,50)

Table 11: Conversion rates between the youth, junior, and senior categories across all swimming events. The colors correspond to a gradient ranging from red, representing the lowest rates, to green, representing the highest rates. The gray color corresponds to conversion rates that are not significantly different from the others.

The insertion rates are presented in **Table 12**. The proportions of juniors from youth ($56,41 \pm 7,58$ %) vs seniors from youth ($34,47 \pm 6,77$ %) are significantly different, as well as seniors from youth vs seniors from juniors ($55,81 \pm 7,27$ %) in all events. When examining the origin of junior

swimmers, the highest insertion rates from youth to juniors are related to female events, especially when the rate significantly exceeds 65%, particularly for short distances (50m-100m). Moreover, the lowest insertion rates of juniors from youth are observed among males. Turning our attention to the insertion rates of seniors from juniors, once again, the highest significant rates, particularly above 70%, are associated with female events. On the other hand, the female 1500m remains the event with the lowest insertion rate (34.26%, 35.11%, 17.02%, respectively for juniors from youth, seniors from juniors, and seniors from youth), regardless of whether it is in a 25m or 50m pool.

Events	Total of Youth	Total of Juniors	Total of Seniors	Juniors from Youth (%)	Seniors from Juniors (%)	Seniors from Youth (%)
1500m freestyle females (25m)	136	148	94	39,19	35,11	17,02
50m breaststroke males (25m)	1751	1565	1989	55,27	39,06	23,93
50m breaststroke females (25m)	2023	1360	1378	68,24	40,35	30,99
50m freestyle males (25m)	2800	2707	3698	53,56	41,54	25,01
800m freestyle males (25m)	718	433	346	51,27	42,77	24,86
50m freestyle females (25m)	3011	2355	2335	67,81	44,71	33,45
200m breaststroke males (25m)	935	896	845	50,89	45,09	25,33
50m butterfly males (25m)	1680	1766	1941	52,15	46,16	26,28
50m breaststroke males (50m)	805	817	872	51,41	46,56	27,29
50m backstroke females (25m)	2009	1390	1191	68,42	46,68	35,85
100m breaststroke males (25m)	1781	1528	1650	56,74	46,79	28,79
100m freestyle males (25m)	2747	2663	2995	54,75	47,55	28,05
50m backstroke males (25m)	1738	1469	1499	59,29	48,10	31,02
1500m freestyle males (25m)	769	751	561	47,27	48,66	25,49
400m freestyle males (25m)	1504	1364	1254	54,40	49,04	29,27
100m butterfly males (25m)	1388	1373	1287	52,15	49,34	29,29
200m breaststroke females (25m)	1093	780	479	65,00	50,73	38,62
1500m freestyle females (50m)	80	108	65	34,26	50,77	20,00
200m butterfly females (25m)	714	588	279	55,44	50,90	29,75
400m freestyle females (25m)	1600	1189	713	63,58	51,75	36,04
100m breaststroke females (25m)	2059	1328	1022	69,88	51,96	39,63
200m freestyle males (25m)	1873	1827	1589	54,79	52,49	31,34
200m butterfly males (25m)	658	709	546	44,57	52,93	26,56
50m butterfly females (25m)	1831	1464	996	66,19	53,21	37,25
200m backstroke males (25m)	926	874	649	54,92	53,31	31,74
50m freestyle males (50m)	1506	1758	1686	47,61	53,80	27,05
100m backstroke males (25m)	1793	1488	1311	61,02	53,93	37,45
200m butterfly males (50m)	206	328	227	34,45	54,19	20,70
100m breaststroke males (50m)	706	735	674	53,33	54,75	31,31
100m freestyle females (25m)	2986	2317	1719	67,20	55,09	39,50
800m freestyle females (25m)	1381	848	379	62,62	55,15	37,20
200m backstroke females (25m)	1052	843	448	60,38	55,36	35,94

50m butterfly males (50m)	914	1162	1078	44,92	56,22	25,97
100m butterfly females (25m)	1546	1142	639	65,50	56,49	38,97
50m breaststroke females (50m)	957	680	547	70,00	56,67	43,14
200m breaststroke males (50m)	366	435	368	48,05	57,34	28,80
200m freestyle females (25m)	2018	1598	920	63,95	57,39	39,13
100m butterfly males (50m)	593	795	595	44,53	57,48	29,24
100m backstroke females (25m)	2060	1453	956	70,13	58,68	45,61
800m freestyle males (50m)	211	280	202	36,07	58,91	25,25
50m backstroke males (50m)	856	875	730	54,40	59,04	36,99
100m freestyle males (50m)	1503	1717	1387	51,19	61,50	32,59
100m backstroke males (50m)	775	796	512	56,91	62,11	40,23
800m freestyle females (50m)	370	354	169	53,95	62,13	34,32
100m breaststroke females (50m)	857	629	416	70,59	62,50	44,95
200m butterfly females (50m)	202	238	104	44,96	62,50	34,62
200m backstroke males (50m)	447	502	297	51,39	62,96	36,70
50m backstroke females (50m)	1036	816	526	67,40	63,31	47,53
200m breaststroke females (50m)	470	393	223	61,58	64,13	43,05
50m freestyle females (50m)	1736	1501	972	65,96	64,40	43,00
1500m freestyle males (50m)	278	308	195	44,48	65,13	30,26
400m freestyle males (50m)	862	801	535	55,31	65,42	39,07
200m freestyle males (50m)	1001	1171	796	50,21	66,21	34,42
100m butterfly females (50m)	618	580	262	58,28	68,32	46,95
50m butterfly females (50m)	995	938	542	61,19	68,63	45,02
400m freestyle females (50m)	873	680	317	65,29	70,66	49,21
100m freestyle females (50m)	1665	1430	752	66,92	71,28	49,07
200m freestyle females (50m)	1092	1018	458	61,30	73,36	45,63
100m backstroke females (50m)	950	769	368	63,85	73,37	51,63
200m backstroke females (50m)	531	474	203	58,02	74,88	44,83
Mean (\pm std)	1200,68 (\pm 599,06)	1055,07 (\pm 488,44)	863,1 (\pm 529, 12)	56,41 (\pm 7,58)	55,81 (\pm 7,27)	34,47 (\pm 6,77)

Table 12: Insertion rates between the youth, junior, and senior categories across all swimming events

The colors correspond to a gradient ranging from red, representing the lowest rates, to green, representing the highest rates. The gray color corresponds to conversion rates that are not significantly different from the others.

In **Figure 31**, the conversions from junior to senior categories at the European Championships, World Championships, and Olympic Games are depicted. 73% of the participants in the junior European Championships do not engage in senior international competitions (**Figure 31**). The other two junior competitions are also affected, with a lower proportion, respectively 51% and 52%, for the junior World Championships and the Youth Olympic Games (**Figure 31**). The reverse is also true. More than half of the participants in the senior European Championships

and World Championships and 37% of Olympic Games athletes had not previously participated in major international competitions as juniors (**Figure 31**). Furthermore, it is noteworthy that few juniors participate in both the Youth Olympic Games and the Olympic Games. 13% of junior swimmers at the YOG represent 5% of senior swimmers at the OG.

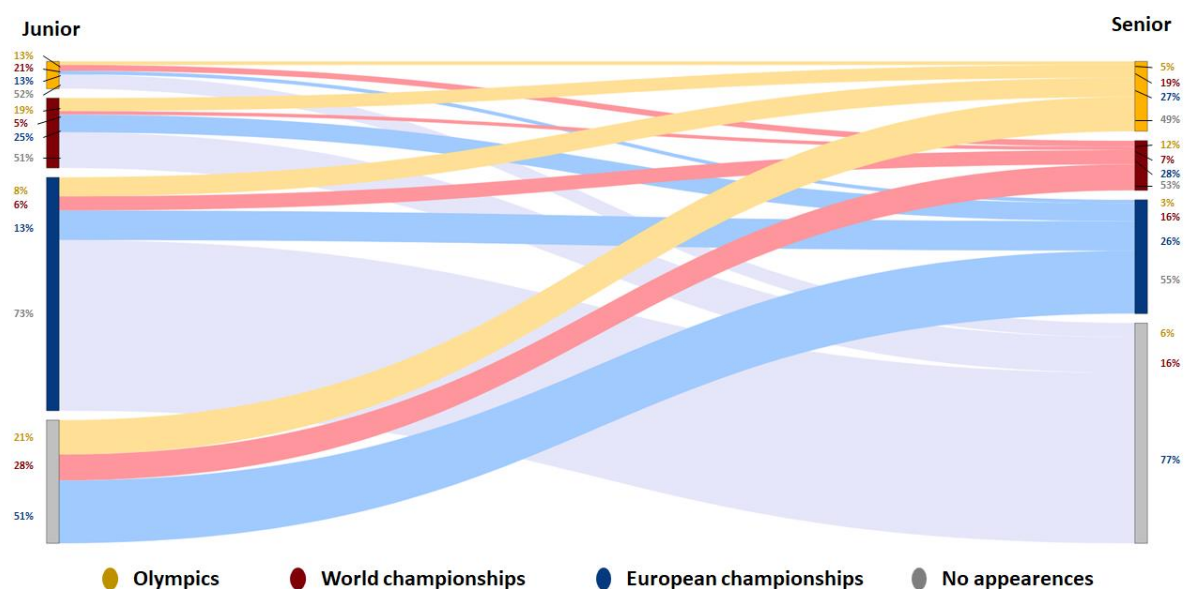


Figure 31: Conversion rates between juniors and seniors in major international competitions

Discussion

This analysis suggests that participating in a youth swimming championship is not a mandatory factor for achieving a participation in the senior swimming championships. Indeed, several studies have examined the impact of junior performances on the future careers of swimmers [281]–[285]. Some have observed that achieving a high level in the junior category is not a necessary condition for success at the senior level [286], [287]. As demonstrated by Yustres et al. [265], where 18% of British junior swimmers participated in the Senior World Championships. They noted that those who reached finals at the Junior World Championships were more likely to participate in the same competition at the senior level, unlike those who stopped at the semi-finals or heats. Consistent with this, Yustres et al. [288] observe that European swimmers who perform well at the Junior World Championships were more likely to medal at the Senior World Championships, emphasizing the positive influence of progression on the likelihood of success at the senior level [289]. Among the 705 swimmers who

participated in both categories, 27% were in the top 10% in both junior and senior levels [289]. They highlighted the importance of experience, with the impact of the number of years of competition on the achieved ranking in various participations in the World Championships [289]. However, they added that female athletes who participated in both junior and senior editions are more likely to achieve a better ranking. Furthermore, as the event distance increased, the proportion of female finalists decreased. This last could align with our results of conversion rates between different categories in female events. Indeed, the conversion rates of the women's 800m and 1500m freestyle events (25m) are among the top 3 events with the lowest conversion rates, across all categories. This analysis suggests that participating in a youth swimming championship is not a mandatory factor for achieving a participation in the senior swimming championships. Indeed, several studies have examined the impact of junior performances on the future careers of swimmers [281]–[285]. Some have observed that achieving a high level in the junior category is not a necessary condition for success at the senior level [286], [287]. As demonstrated by Yustres et al. [265], where 18% of British junior swimmers participated in the Senior World Championships. They noted that those who reached finals at the Junior World Championships were more likely to participate in the same competition at the senior level, unlike those who stopped at the semi-finals or heats. Consistent with this, Yustres et al. [288] observe that European swimmers who perform well at the Junior World Championships were more likely to medal at the Senior World Championships, emphasizing the positive influence of progression on the likelihood of success at the senior level [289]. Among the 705 swimmers who participated in both categories, 27% were in the top 10% in both junior and senior levels [289]. They highlighted the importance of experience, with the impact of the number of years of competition on the achieved ranking in various participations in the World Championships [289]. However, they added that female athletes who participated in both junior and senior editions are more likely to achieve a better ranking. Furthermore, as the event distance increased, the proportion of female finalists decreased. This last could align with our results of conversion rates between different categories in female events. Indeed, the conversion rates of the women's 800m and 1500m freestyle events (25m) are among the top 3 events with the lowest conversion rates, across all categories.

This observation of a low conversion rate is also true regarding all sports, where a low conversion rate is found, with approximately only one-third of international junior succeeding

at the elite senior level [130]. The finding is similar in Gulbin et al. [290], with a conversion rate of less than 7% across 27 different sports for a small sample of 256 elite athletes. This could be because athletes' performance trajectories fluctuate and are relatively unpredictable before the junior category [290], as suggested by Costa et al., possibly due to the low stability of male freestyle performances [271]. This is why some research advocates for focusing more on the progression of swimmers rather than current performances achieved [291], [292]. This aligns with what Allen et al. (2014) state about the primary goal of talent identification programs, which is to identify athletes with high potential who will succeed at the senior level [283]. The finding is similar in Gulbin et al. [290], with a conversion rate of less than 7% across 27 different sports for a small sample of 256 elite athletes. This could be because athletes' performance trajectories fluctuate and are relatively unpredictable before the junior category [290], as suggested by Costa et al., possibly due to the low stability of male freestyle performances [271]. This is why some research advocates for focusing more on the progression of swimmers rather than current performances achieved [291], [292]. This aligns with what Allen et al. (2014) state about the primary goal of talent identification programs, which is to identify athletes with high potential who will succeed at the senior level [283].

Limits

In the junior-senior conversion, to avoid having the same individual participate in multiple competitions of the same category, we chose to prioritize the competitions. First, we placed the Olympic Games, followed by the World Championships, and finally the European Championships. Some athletes were able to participate in all the competitions. However, they will only appear in the most prestigious competition.

Furthermore, we restricted our analysis to examining only the conversion rates in terms of participation. Future research is needed to observe the conversion rate among medalists or the significance of the age at which the first senior medal is achieved, as demonstrated by Rees et al. in their study on variables distinguishing medalists at major international competitions from less prestigious ones [220]. Furthermore, we restricted our analysis to examining only the conversion rates in terms of participation. Future research is needed to observe the conversion rate among medalists or the significance of the age at which the first senior medal is achieved,

as demonstrated by Rees et al. in their study on variables distinguishing medalists at major international competitions from less prestigious ones [220].

Conclusion and practical applications

In this study, we observe that conversion rates are low, particularly in certain women's long-distance events. However, the highest conversion rates are seen from the junior to senior category. Therefore, this study provides insights to enhance potential identification and development programs to find ways to achieve medals in both junior and senior categories. This information could be especially useful for coaches in their planning, guiding them toward Olympic gold by assisting in better aligning short-term goals for athletes.

GENERAL DISCUSSION

Main contributions to the field

This work identifies a relative age effect among French swimmers and athletes, which becomes more pronounced as the level of performance increases. We propose a valid rebalancing method that helps better assess the athlete's performance considering their exact age. This is achieved through a coefficient based on sex, discipline, and the strength of the relative age effect within the relevant category. Indeed, age is an imperative parameter to consider as it has an impact on the athletes' future engagement in the sports' practice. Whether female swimmers dropping out around the age of 13 or male swimmers around 17, the consideration of birth quarters has proven relevant. As we have observed, swimmers born later in the year are more likely to drop out than those born earlier in the year.

However, another aspect related to age parameter has been highlighted: biological age at PHV. Investigating the link between maturation and performance at the French Junior Championships in swimming in 2022, we found that the most mature swimmers are more likely to perform better. Conversely, those who performed poorly were disproportionately frequent among the less mature individuals. When looking on a wider scale at the trajectory of juniors and youth regardless of the level of maturation, we observe that only a few of them reach a high senior level. The conversion rate from junior to senior in major international competitions remains low.

In this regard, my thesis aimed to bring forth new variables to be considered, moving away from performance-based selection and toward potential estimation. Moreover, with an applied perspective in mind, this work intends to raise awareness among sports professionals about the hidden issues posed by current performance-based selection. By better appreciating individual data, it becomes possible to enhance current detection techniques.

Field application of performance recalibration

We observed the presence of a relative age effect within the young French athletes and swimmer population, with its impact becoming more pronounced as performance levels rise in accordance with previous studies [8]. However, this effect diminishes as athletes progress through different age groups, effect also demonstrated by other studies [106], [229]. It is indeed challenging to make substantial improvements when already operating at an advanced level. Furthermore, at such elite tiers, only the most exceptional individuals persist, regardless of their birth month.

Currently, the French Swimming Federation partially applies this recalibration in the youth category to establish qualification times for the French Championships, distinguishing between individuals born in the first and second semesters of the year. While there is no immediate plan to implement a comprehensive theoretical rebalancing for all performance metrics, event organizers are considering incorporating the RAE considerations into youth competitions. By hosting two sessions of the French Youth Championships, the federation aims to mitigate the impact of the RAE on this competition by adjusting the qualification times for individuals born in the second semester. This adjustment can be made based on the times achieved during the first session of the competition. The differences in times between individuals born in the first semester and those born in the second semester are presented in **Table 13** and **Table 14** by event and by sex for the 13-year-olds.

Event	Sex	Age	Average time S1	Average time S2	Coefficient
50 Freestyle	Female	13	29.603	29.644	0.041
100 Freestyle	Female	13	64.397	64.612	0.215
200 Freestyle	Female	13	138.844	139.429	0.585
400 Freestyle	Female	13	291.815	292.431	0.616
800 Freestyle	Female	13	600.8	603.848	3.048
1500 Freestyle	Female	13	1100.811	1112.336	11.525
50 Backstroke	Female	13	33.886	33.923	0.037
100 Backstroke	Female	13	72.466	72.786	0.32
200 Backstroke	Female	13	153.193	153.8	0.607
50 Breaststroke	Female	13	38.111	38.276	0.165
100 Breaststroke	Female	13	82.304	82.522	0.218
200 Breaststroke	Female	13	174.08	174.629	0.549

50 Butterfly	Female	13	32.315	32.384	0.069
100 Butterfly	Female	13	71.812	72.027	0.215
200 Butterfly	Female	13	159.045	159.48	0.435
100 IM	Female	13	74.495	74.645	0.15
200 IM	Female	13	157.581	157.945	0.364
400 IM	Female	13	330.733	332.367	1.634

Table 13: Average performance comparison between female swimmers born in the first semester and female swimmers born in the second semester across all events

(S1: Semester 1, S2: Semester 2).

Event	Sex	Age	Average time S1	Average time S2	Coefficient
50 Freestyle	Male	13	27.692	27.785	0.093
100 Freestyle	Male	13	60.349	60.703	0.354
200 Freestyle	Male	13	131.254	132.118	0.864
400 Freestyle	Male	13	277.215	278.286	1.071
800 Freestyle	Male	13	572.894	576.333	3.439
1500 Freestyle	Male	13	1083.912	1082.602	1.31
50 Backstroke	Male	13	31.927	32.143	0.216
100 Backstroke	Male	13	68.433	68.979	0.546
200 Backstroke	Male	13	145.053	145.893	0.84
50 Breaststroke	Male	13	35.651	35.989	0.338
100 Breaststroke	Male	13	77.367	77.88	0.513
200 Breaststroke	Male	13	165.166	166.604	1.438
50 Butterfly	Male	13	30.202	30.405	0.203
100 Butterfly	Male	13	67.207	67.767	0.56
200 Butterfly	Male	13	148.922	150.17	1.248
100 IM	Male	13	69.656	70.117	0.461
200 IM	Male	13	148.846	149.844	0.998
400 IM	Male	13	313.558	315.708	2.15

Table 14: Average performance comparison between male swimmers born in the first semester and male swimmers born in the second semester across all events

(S1: Semester 1, S2: Semester 2).

We managed to offer a solution to mitigate the relative age effect and equalize performance metrics in track and field and swimming. Furthermore, the RAE appears to manifest itself in popular sports [48], [79]. Swimming ranks 8th among sports with the highest number of registered participants in France, while track-and-field struggles to break into the top 10. In their study involving a population of over 13,000 girls across 34 different sports, Gil et al. observed that the RAE is most evident in basketball, which is the most popular sport among

girls, with a participation rate of 28.1% [48]. Conversely, among boys, the strongest RAE is observed in soccer with a participation rate of 57.4%, stemming from an initial pool of nearly 25,000 boys across 36 different sports [48]. These findings tend to align with observations made by the authors in relation to rugby in the UK [68], ice hockey in Canada [293], and handball [76] in Germany. However, the second most participated sport among girls, gymnastics, shows no signs of RAE, consistent with previous studies on artistic sports [37], [86], [97] highlighting the need to also consider the specificities of each sport. Moreover, we can ponder over the influence of a sport's popularity on its competitiveness. It is plausible to assume that as the number of participants increases, so do the disparities among practitioners, resulting in heightened competitiveness within the sport. Thus, a sport's popularity could impact its competitiveness and then RAE. This is consistent with our results where RAE increases with the level of competition.

As we saw, the relative age effect also manifests in team sports [235], as evidenced by the Pôle France basketball academy, where no female junior athlete was born in the fourth quarter (**Figure 12**). These results are consistent with those of Delorme et al. [294] concerning French female basketball players and with Arrieta et al. [294] concerning French female basketball players and with Arrieta et al. [44] regarding a larger population at the U16 and U18 European Basketball Championships. However, Lidor et al. [34] do not observe a significant RAE in a smaller population, although 18% of the team is still born in the last quarter of the year.

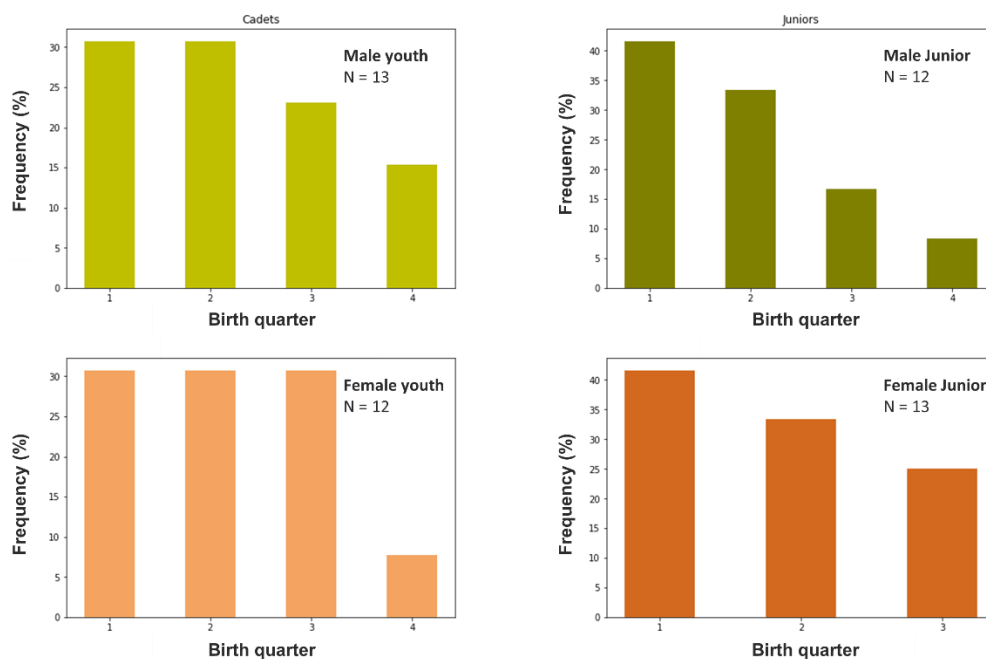


Figure 32: Distribution of birth quarters among male and female basketball players of the Pôle France basketball academy (INSEP) during the 2021-2022 season

However, to our knowledge, no study has applied rebalancing methods to a team sport like basketball. The challenge lies in evaluating team sports, especially at an individual level within a team. This complexity makes rebalancing a challenging task. However, we believe that it is not beyond reach. We suggest to consider young athletes to physical assessments and then correlate these evaluations with their actual match performance. Individual match performance can be quantified using metrics like the Performance Efficiency Ratio (PER) [295], extensively utilized in the NBA to gauge a player's impact during a game. Once we identify the most influential physical parameters for performance, we could recalibrate the outcomes of these assessments since they yield metric outcomes. Nevertheless, to achieve a reliable regression and a representative coefficient for our population, a sufficient number of test results are imperative.

As was the case in rowing, we utilized the 2000-meter ergometer time trial, which happens to be widely recognized as an excellent indicator of performance in rowing [296], [297]. As a result, we were able to analyze the RAE among French rowers. To our knowledge, there is no study on the RAE in rowing in France and even in Europe. We were able to highlight a relative age effect with a proportion of rowers born in the first quarter of the year significantly higher

than the proportion of rowers born in the last quarter of the year, both for girls and boys (Figure 29).

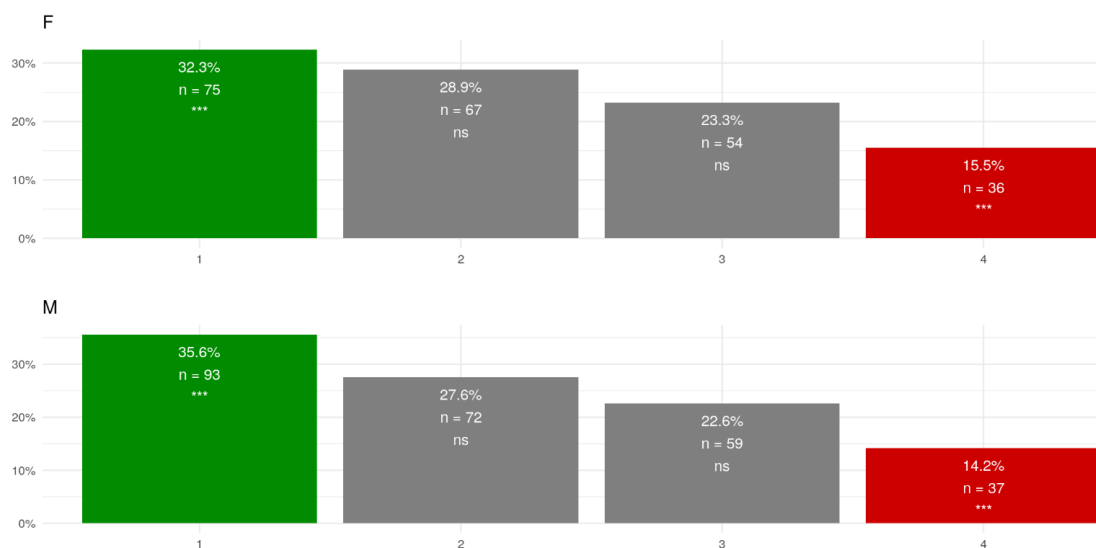


Figure 33: Birth quarter distribution among male (M) and female (F) French rowers

By calculating the rebalancing coefficients on ergometer test performances, it is possible to achieve rebalancing. It is worth noting that the absolute value of the coefficient decreases significantly from -2.43W to -1W per month, respectively from 15 to 18 years old (Figure 30).

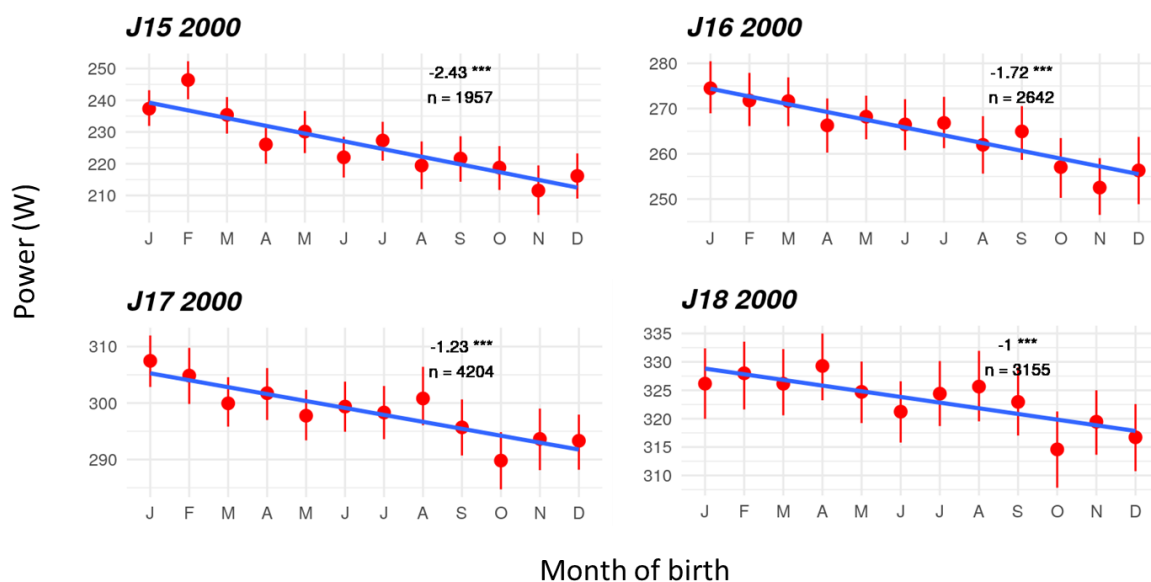


Figure 34: Rebalancing coefficients by month of birth in French rowing

(J15: 15-years-old group, J16: 16-years-old group, J17: 17-years-old group, J18: 18-years-old group, ***: p-value<0.001)

By rebalancing the performance based on the coefficient, it can no longer be said that there is a relative age effect among the rebalanced performances as the coefficient are no longer significant (Figure 35).

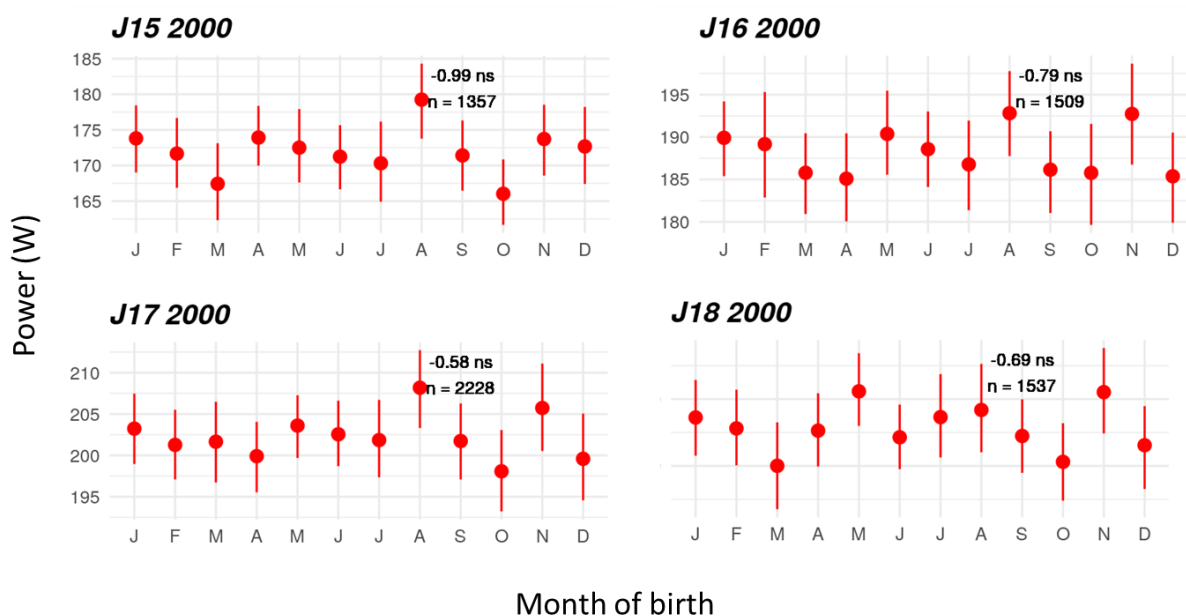


Figure 35: Post-rebalancing coefficients by month of birth in French rowing

(J15: 15-years-old group, J16: 16-years-old group, J17: 17-years-old group, J18: 18-years-old group, ns: non-significant)

These analyses represent the first application of rebalancing methods to a sport, even though it is a metric sport with varying weather conditions for each race.

Possible dropout origins

Investigating the dropout rates among athletes adds an intriguing dimension, as it validates the insights previously held by coaches and federation members. These insights pertain to the age at which dropouts occur and the sex-based variations in dropout rates. Armed with these statistics, federations are better equipped to address the issue of young athletes discontinuing their participation in sports and to formulate strategies to sustain their motivation. As demonstrated, individuals born in the final quarter of the year exhibit a higher likelihood of dropping out. It is noteworthy that insufficient performance levels among categories contribute to dropouts [124], making rebalancing a plausible remedy for retaining prospective participants within the detection pathways. As shown in **Figure 36**, swimmers who drop out tend to belong, on average, to the lower performance deciles. On the other hand, those who do not drop out appear to have a more evenly distributed distribution of performance deciles. This highlights that the pursuit of performance can be a driving factor in swimming practice.



Figure 36: Best performance deciles achieved by those who dropped out and those who continued swimming practice.

Moreover, it has been observed that the age at which there is a notable dropout among girls is typically around 13 [298]. This timing corresponds to the onset of menarche [164]. The transformations and developments occurring within the body due to maturation can potentially present a hurdle in the context of swimming [259]. It is plausible that girls may

experience discomfort with changes in their body shape and subsequently choose to discontinue their participation in a sport that necessitates wearing a swimsuit. If a young girl is not comfortable with her appearance, it can have negative implications on her well-being and health [259]. This underscores the significance of promoting understanding about the importance of maturation, self-acceptance, mutual respect, and the advantages of engaging in sports [299]–[302]. The transformations and developments occurring within the body due to maturation can potentially present a hurdle in the context of swimming [259]. It is plausible that girls may experience discomfort with changes in their body shape and subsequently choose to discontinue their participation in a sport that necessitates wearing a swimsuit. If a young girl is not comfortable with her appearance, it can have negative implications on her well-being and health [259]. This underscores the significance of promoting understanding about the importance of maturation, self-acceptance, mutual respect, and the advantages of engaging in sports [299]–[302].

Towards better estimation of maturation

The current assessment of physical maturation through the Mirwald method comes with inherent limitations. As one moves further away from the age of peak maturity, the accuracy of the age difference at peak diminishes [303], [304]. Among the swimmers participating in the French junior championships, only a few were either approaching or yet to reach their peak maturity. We were aware that the estimate might not be highly accurate, as the authors acknowledge, the maturity offset could be estimated within an error of a year, 95% of the time [165]. Yet, we sought to gain a general understanding of the athletes' maturation status in relation to their peak: whether it occurred before, during, or after the event.

However, we aimed to enhance the precision of this age-at-peak estimate even though studies demonstrate that is not an easy task [305], [306]. Using the same databases as Mirwald, Moore et al. provide a new equation with the same level of accuracy, but simpler, as it omits the need for sitting height measurements, thereby making age estimation at PHV more accessible [169]. However, a similar error level was observed in the calculation of maturity offset [169]. Conversely, when applied to a different dataset of young footballers, a reduction in error was observed due to the reduction of variables [306]. According to their comparison, Moore's equation exhibited the highest precision rate compared to Khamis-Roche estimations [307] that rely on parental birth dates [306]. While Mirwald's equations offer a broad perspective, individual growth trajectories exhibit variations despite following a common trend. By definition, peak maturation triggers accelerated growth, with maximal growth occurring at the time. Therefore, by regularly collecting data on standing height, sitting height and body mass, it becomes possible to discern shifts in the pace of growth. This change in growth pattern is indicative of the peak which varies individually in terms of timing and tempo. However, gathering sufficient data on individual standing and sitting heights, as in mass is imperative for a real-time estimation to be developed. The height data of male and female basketball players who have gone through the Pôle France basketball academy are respectively depicted on the left and right of **Figure 37**. However, considering the discrepancies in height that sometimes exist at the same age, it can be assumed that measurement errors are present. When observing the ages at which measurements were taken, they were not at regular intervals. Yet, for accurate tracking, regular intervals are essential. By taking measurements of height, sitting

height, and weight recorded 2-3 times per year, it becomes feasible to track yearly increases in height and weight, thereby individually determining the age at PHV. On the other hand, we notice that height growth is less pronounced in females compared to males, with a generally flatter curve trend. This reflects a difference in the timing of the peak height velocity (PHV) between females and males, with the PHV occurring a few years earlier in females [164].

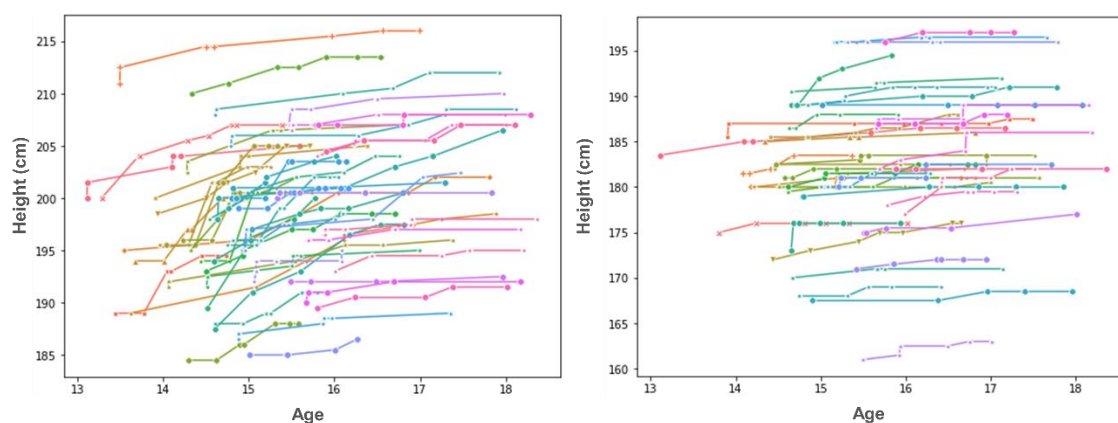


Figure 37: Height of male (left) and female (right) basketball players from the Pôle France basketball academy since 2017 according to age.

There is also a different approach that is interesting with biological age. Even though it is strongly correlated with chronological age as we have seen previously through its calculation, it could be relevant to assess performance in relation to this variable. **Figures 38 and 39** present two different approaches to assessing swimming performances, respectively using chronological age and biological age. In **Figure 38**, we might get the impression that when comparing them at the same chronological ages, the individual on the blue curve performs better than the other swimmers. However, when adopting the perspective of biological age, it seems that the individual on the red curve achieves better performances (**Figure 39**).

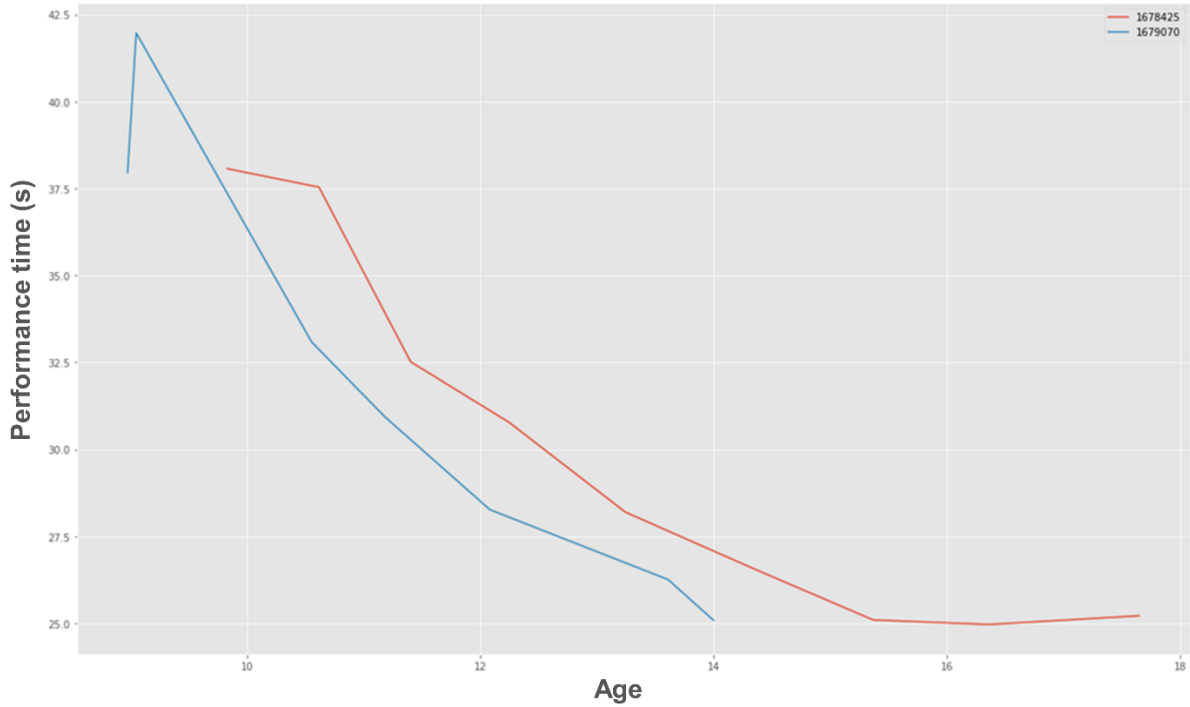


Figure 38: Performance times in swimming of two junior male individuals in the 50m freestyle event in a 50m pool, based on chronological age.

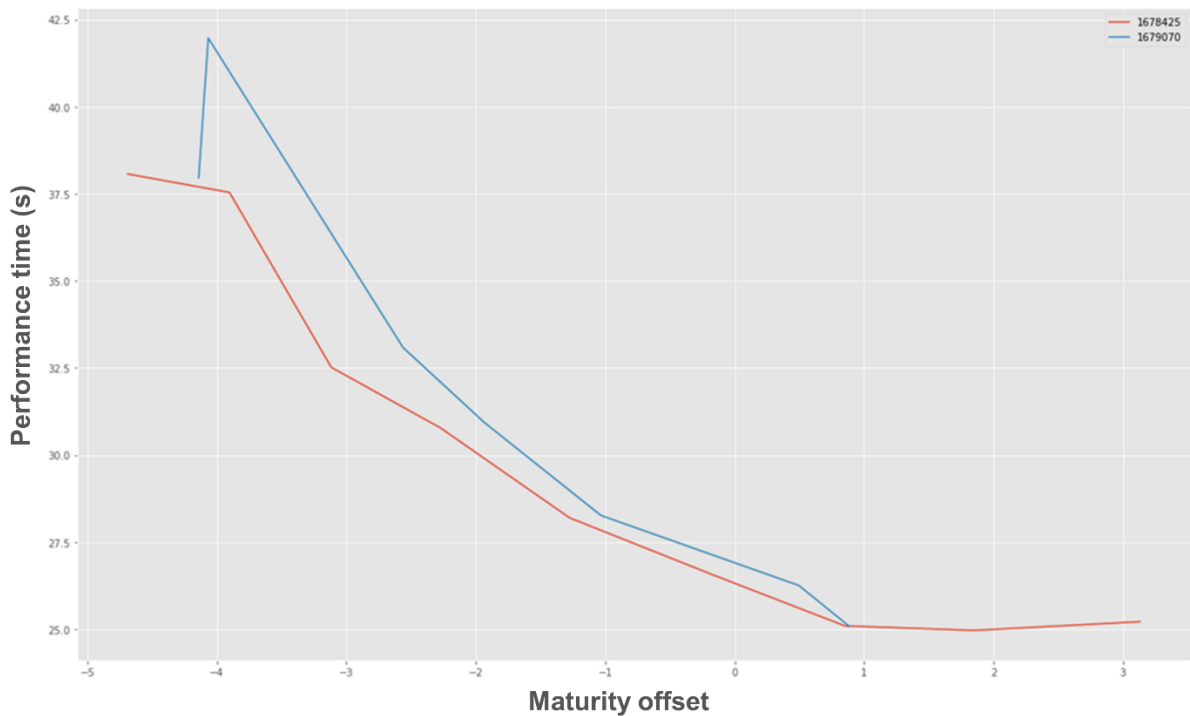


Figure 39: Performance times in swimming of two junior male individuals in the 50m freestyle event in a 50m pool, based on maturity offset.

The latter has also passed his PHV for a longer time, and his performances have been relatively stable for the past 2 years. However, his counterpart, who is almost 4 years younger, seems to

be in a progression phase. It is also important to keep in mind that these two individuals compete in the same category and the same competition, despite their age difference. That is why it is necessary to consider all the individual components specific to each person, starting with the different types of age, chronological and biological, to contextualize performance.

When comparisons between athletes are involved, the elements of comparison and the context should be opened up to other variables such training age, sociological or psychological variables [234].

Sex disparities

Throughout these studies, we have observed the significance of sex during the analyses. When investigating the RAE, higher proportions of births in the first quarter of the year are observed among male athletes, as well as a stronger relative age effect coefficient. As demonstrated in the 100m event, boys in the U13 category exhibit a mean performance difference delta of 0.931s per year, compared to a delta of 0.564s among girls in the same age category. No study in literature has calculated a relative age effect coefficient and consequently balanced girls and boys in the same event before the age of 15. Previous research has focused on the 100m Freestyle in Australian boys [8], the 100m and 200m breaststroke in females [104], and the 60m sprint in Swiss males [237]. The study by Brustio and Boccia examines male and female sprinters (100m, 200m, 400m) in the junior world level category [89]. There seems to be a slight distinction between the 16-year-old and 17-year-old categories, with this difference tending to increase proportionally with distance [89]. Indeed, among the athletes of the 16 years old age category, there is a -2.02% vs -1.66% performance difference respectively for males and females 100m, as well as a -2.23% vs -1.65% performance difference respectively for males and females 400m [89]. A study has revealed a gender-related discrepancy in terms of the age at which peak performance is achieved [308]. Due to earlier onset of puberty in females, their physiological peak is attained 2 to 3 years earlier [180], [309]. As performance hinges on physiological capacities, differences in the age of reaching these full physiological potentials could contribute to disparities in ages of peak performance. This divergence is also present in the mean age of female Olympic gold medalists, who are generally 1 to 2 years younger than their male counterparts [178]. Similarly, in tennis, the pinnacle percentage of victories for the top 10 female players is reached around age 21, in contrast to age 24 for male players [187].

Sex differences are also observed in the study of dropout rates. Firstly, regardless of performance, the age at which girls drop out the most is at 13 years old, whereas for boys, it occurs at 17 years old. Additionally, using survival curves, we can distinguish a significant gap in the probability of dropout after 15 years old. We can speculate that maturity has a greater negative impact on girls than boys. Several explanations are possible. The earlier arrival of PHV in girls compared to boys [164] and its consequences could explain this difference. The processes of maturation and growth bring about morphological changes in muscles, bones, and

tendons [260]. The body needs to adapt to these new developments, sometimes putting certain parts of the body at risk, which are quite fragile during this time window [310], [311]. Hence the importance of diversification and various muscle solicitations to address these shortcomings. However, sports often have particular solicitations, and in this sense, the sport can have repercussions on the morphology of the young individual, through maturation and growth, which are individual to each person. Moreover, studies show that the menstrual cycle has an effect on performance [312]–[317]. The processes of maturation and growth bring about morphological changes in muscles, bones, and tendons [260]. Hence the importance of diversification and various muscle solicitations to address these shortcomings. However, sports often have particular solicitations, and in this sense, the sport can have repercussions on the morphology of the young individual, through maturation and growth, which are individual to each person.

Given that good performance and success have a significant factor in continuing sports practice, this implies that the menstrual cycle could as well [124]. However, to date, no study has examined this question and the impact of cycle symptoms on a population of young girls. Nevertheless, cycle irregularities have been observed in a high school population during the first 5 years of the cycle [318]. Additionally, girls experience a greater increase in body fat than boys [17]. This has an impact on the body image they have of themselves and therefore on their willingness to continue with sports [259].

What about senior level

In this thesis, our investigation extended to the performance records of young athletes up to the age of 18. However, researchers have investigated the relative age effect at the senior level in elite competitions. In a study centered on basketball participants during the London 2012 Olympic Games, a noteworthy relative age effect was identified solely within the French team. A remarkable 66% of the squad members were born in the first semester, including 54% in the second quarter [56]. The authors used the Q2 population, which surpasses that of the other quarters, to support the existence of a relative age effect [56]. Nonetheless, considering the p-value exceeding 5%, it remains uncertain whether a relative age effect was genuinely present or not [56]. In this context, although the effect was not statistically significant, it is noteworthy that 80% of Lithuanian players, 63% of Brazilians, 58% of Nigerians, and 57% of Argentinians were born in the first half of the year [56]. However, revisiting the context of Olympic swimming during the London Games, Ferreira et al. [82] point out that a relative age effect (RAE) was observed exclusively among Asians, along with a higher proportion of girls in the 1st and 3rd birth quarters. Similarly, focusing on female athletes participating in the Summer Olympic Games, this time in football, a subtle RAE emerged from the Beijing 2008 Games onward [82]. Notably, there was a slightly decreased number of girls born in the last quarter of the year compared to the other three Games (22%, 19%, 19% in 2008, 2012, and 2016, respectively) [319]. This phenomenon extended to Spanish female Olympians between 2004 and 2012, while their male counterparts did not exhibit such an effect. Conversely, Australian athletes across various sports did not demonstrate a RAE either [320].

The findings regarding the senior RAE are not consistent across studies. However, when it comes to the junior-senior conversion rate, the literature generally agrees, indicating relatively low numbers. In this context, to investigate high-level performance indicators, Güllich et al. focused on differentiating two categories of high-level athletes: those achieving medals in major international competitions (super-elite) and those not achieving medals (elite) despite their dedication and performance [321]. They matched 16 super-elite athletes with 16 elite athletes in the same sport, discipline, sex, age, and career period [321]. A questionnaire covered various aspects related to performance, including personality traits, psychological skills, motivations, birthplace significance, family support, and sports practice [321].

Parameters distinguishing super-elite from elite athletes included living locations, participation in high-level championships, experiencing early negative events in sports, age differences, sibling rivalry, family culture of effort and success, higher supervised and unsupervised physical activity, need for achievement, and self-evaluated obsession or perfectionism [321]. This aligns with the variables highlighted by Williams et al. [234] in soccer talent identification and detection as predictors of high performance among seniors, encompassing four primary themes: physical, technical, sociological, and psychological aspects [234]. There are also four secondary themes involving maturation, developmental environment, external influences, and chance-related events, which include factors like birthdates, birthplaces, and other life events [234]. This underscores that predicting performance and success in high-level sports remains intricate and a vast research domain.

Limits

During the recalibration process, we propose employing linear regression to calculate the coefficient associated with relative age within the age group. However, other researchers use a polynomial approximation applied to the entire set of study performances [8], [88], [89], [104], [237]. It is true that better modeling options exist, with individual-level models being the most optimal for estimating future performances based on age [322]. Nevertheless, this method requires a sufficient amount of data per athlete to achieve accuracy and proves less feasible for implementation by coaches or federations. The advantage of using linear regressions here aligns with the goal of obtaining coefficients for each age category that are independent of the preceding and following age categories. Indeed, it was crucial for each coefficient to capture the essence of RAE within its age category. In contrast to previous studies aimed at reducing or eliminating RAE within their sample through rebalancing [8], [88], [89], [104], [237], our primary objective was to uncover potentially hidden potentials due to RAE. During the recalibration process, we propose employing linear regression to calculate the coefficient associated with relative age within the age group. It is true that better modeling options exist, with individual-level models being the most optimal for estimating future performances based on age [322]. Nevertheless, this method requires a sufficient amount of data per athlete to achieve accuracy and proves less feasible for implementation by coaches or federations. The advantage of using linear regressions here aligns with the goal of obtaining coefficients for each age category that are independent of the preceding and following age categories. Indeed, it was crucial for each coefficient to capture the essence of RAE within its age category. In contrast to previous studies aimed at reducing or eliminating RAE within their sample through rebalancing [8], [88], [89], [104], [237], our primary objective was to uncover potentially hidden potentials due to RAE.

Moreover, to estimate the maturation of swimmers, we employed the equations developed by Mirwald [165]. However, these equations were based on fewer than 160 data points from Canadians and validated on fewer than 100 Flemish individuals who not only were not high-level athletes but also constituted a Caucasian population. In the same vein, Moore derived his equations from the same population [169]. We opted to use Mirwald's equations as we did not observe any significant differences compared to Moore's equation values. Nevertheless, it is

essential to bear in mind that these are estimations, and they become less reliable as we move away from the PHV [303], [304]. Also, their accuracy is quite approximate due to the unique characteristics of each population [323]. This aspect also relates to the limitations regarding performance estimation.

In contrast to other studies with a sizable population, the analysis of the Junior French Championships is based on a small sample. Following discussions, exchanges, and insightful feedback from the French Swimming Federation, the project aims to extend the consideration of maturation to a broader and younger population, the youth category. As a result, in order to overcome these last two limitations, data collection from youth swimmers entering in training centers will be initiated.

Furthermore, the study on conversion and insertion rates should be extended to major competitions across all sports to develop assessment tools for the detection and selection programs that are implemented. Additionally, in this study, there were instances where some athletes participated in all junior or senior competitions, but we considered only their participation in the most prestigious competition. A method needs to be devised that retains all the competitions they participated in and also incorporates a notion of relative performance to observe whether or not it correlates with conversion and entry rates.

Finally, we observed large populations of young athletes in swimming and athletics, with entry criteria being possession of a license and participating in competitions. Moreover, it becomes more complicated to apply this method to other non-metric sports, more artistic disciplines, or those subject to judges' evaluations (such as gymnastics, synchronized swimming, or diving).

Strengths

In the studies we have conducted, we have worked with significant and exceptionally reliable databases. Thanks to the substantial populations in athletics and swimming, and the data collection efforts spanning 13 and 23 years respectively, our analyses are robust. Not only are the results statistically significant as a whole, but the techniques used are scientifically valid, given the validation methods tested and approved on real athlete data. Indeed, concrete solutions have been proposed. They are applicable in real-world scenarios, as demonstrated during the Junior French Championships held this year. The diversity of sports covered also contributes to the strength of this thesis. Indeed, with the performance rebalancing applied to metric sports and the perspectives from basketball applicable to team sports, this covers a wide spectrum of sports.

Finally, these studies mark the initial steps towards transitioning from detection to potential estimation. We have highlighted the impact of the RAE and provided a solution to better address it through age, sex, and event-based rebalancing. Federations can absorb these findings and apply them to their respective sports. Once this step is taken, based on the available data and maturation estimations, this thesis equips federations to estimate a PHV at a given time during their testing sessions or competitions to understand the influence of maturation on performance. The studies on dropout, considering the impact of birth month and performance, as well as the conversion rates from junior to senior, highlight the multifactorial complexity of achieving future performance. This underscores the necessity to investigate the life trajectory of elite athletes.

Perspectives

The ultimate goal is to estimate potentials. To achieve this, we would like to establish a scientific model based on the variables described throughout this manuscript. It could be interesting in this context to prospectively follow different cohorts of young athletes from various sports to, firstly, gather data to feed the model and, secondly, to test and validate different models.

The next steps of this work have already been initiated, notably through the estimation of potentials among French skiers [322]. Indeed, by reasoning at the individual level, the objective is to estimate future performances and even the trajectories these performances will be based on collective modeling of all skiers. Similarly, these efforts are currently being applied to swimming data. To delve deeper and enhance these models, we are working on a questionnaire aimed at collecting data on the life trajectories of high-level swimmers who have participated in major competitions. Potential indicators of high-level performance in football identified by Williams et al. initially served as inspiration for this questionnaire (**Figure 40**) [234].

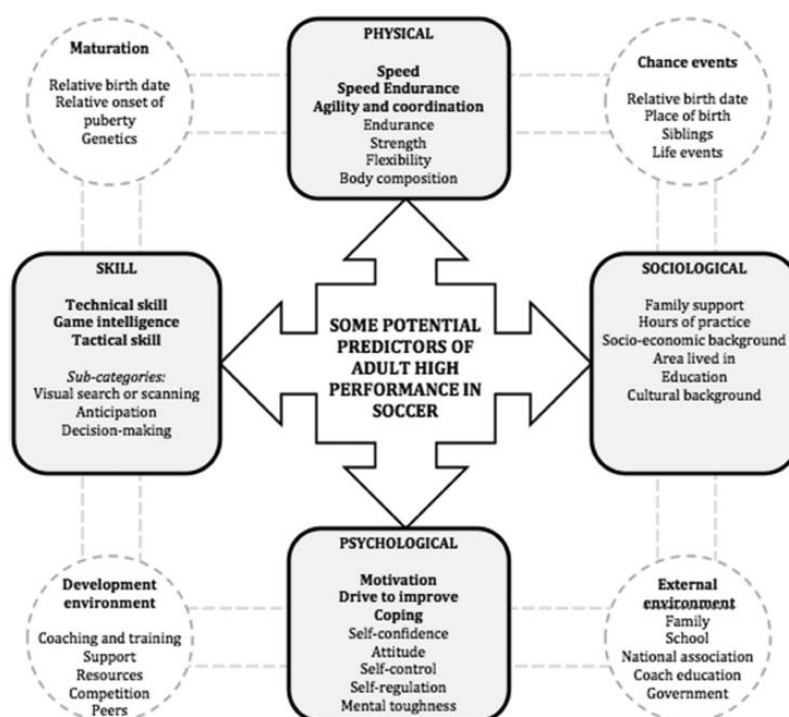


Figure 40: Potential predictors of adult high performance in youth soccer players from each sports science discipline, with mediating factors.

(From Williams et al., 2020 [234])

Indeed, various variables, encompassing sociological, psychological, and physical aspects, will be investigated. Numerous studies emphasize the significance of family support and the role of parents in the engagement and success of young athletes in sports [324]–[329]. From a psychological point of view, self-confidence [330], stress management [331], motivation [332], and cognitive development [333] through concentration, strategic planning, and rapid decision-making have been identified as influencing performance. Another study that significantly influenced this questionnaire is the study conducted by Güllich et al. [321], which encompasses these 8 themes:

- Demographics: place of residence, birthplace, educational institutions;
- Family: parents' and siblings' sporting backgrounds;
- Significant ages in the sports career: at the beginning of practice, first competitions, first medals, and records;
- Competitions: specialty swim, number of competitions between two ages or within an age category
- Psychosocial characteristics
- Practice volume: coached and uncoached practice within a club or in other sports, proportion of practice in different sports skills
- Athlete services: use of various treatments, preparations, performance analyses
- Traumatic events: number of injuries, non-selections for national teams, underperformances or failures.

Indeed, the objective is to better contextualize the performance trajectories of high-level French swimmers and to quantify the impact of other parameters than fixed performances at a given moment, on international successes. The study population will consist of all French swimmers who have participated in continental (European Championships) and global (World Championships and Olympic Games) competitions up to the present day. After collecting performance data, rankings in various international competitions, and responses to questionnaires, the study population will be stratified into two groups: medalists vs. non-medalists. Their questionnaire responses will be analyzed to highlight significant differences between the two groups. We hypothesize that the two groups will have different characteristics. From there, we will attempt to identify young swimmers who possess the

characteristics corresponding to the group of medalists. Finally, we will attempt to adapt and enhance the questionnaire and the model in order to transfer it to all sports.

CONCLUSION

In conclusion, this work demonstrated the influence of relative age and biological age on the performance of young French athletes and swimmers. Firstly, concerning the relative age effect and dropout rates, it is clear that those born later in the year are disadvantaged compared to their older counterparts born earlier in the year. Not only do they, on average, achieve lower performances, but they also have a higher likelihood of dropping out compared to those relatively older within the same age category.

Secondly, our findings highlight a positive effect of biological age on high-level performances among juniors. However, when we focus on this young population, we observe that among those who reach the top level as juniors, only a few manage to maintain their level as seniors.

The framework derived from this thesis also provides insights for transitioning from performance detection and selection towards potential estimation through a holistic approach centered in young athletes. Indeed, various factors can influence the athletic performances and the progression of a young athlete. Therefore, it is crucial to consider morphological, psychological, sociological, technical elements for a more accurate and fairer assessment of the potential of young individuals.

SYNTHESE

ESTIMATION DE POTENTIELS CHEZ LES JEUNES ATHLETES

ETAT DE L'ART

La question de l'identification des talents dans le sport est très complexe. En effet, l'objectif est d'identifier, détecter et choisir les futurs champions olympiques 10 ans à l'avance. A ce titre, l'âge est l'un des facteurs clés, parfois sous-estimé, dans cette quête. Plus jeune un athlète est identifié, plus il aura de temps pour se développer dans des structures de haute performance. Pour cela, les fédérations tentent au mieux d'améliorer leur technique de détection et de sélection pour trouver les futurs champions. Ce sont deux processus bien distincts. La détection désigne l'art de repérer ou d'identifier des futurs champions sans signes apparents de réussite. En effet, l'objectif est de « déceler l'existence de ce qui est caché afin de tenter de savoir si, parmi une grande population de jeunes enfants, sportifs ou non, certains d'entre eux ont plus de chances d'acquies à long terme, les capacités requises par l'exercice d'un sport au plus haut niveau au moment où ses capacités atteindront leur développement optimal ». La sélection, quant à elle, arrive après la détection et consiste à choisir des meilleurs sportifs parmi un ensemble afin de participer à une épreuve, une compétition, un regroupement ou un stage d'entraînement. Les sélectionneurs se basent sur différentes caractéristiques afin d'effectuer les meilleurs choix. En fonction de l'âge, ces caractéristiques évoluent et ne sont pas toujours les mêmes.

Effet de l'âge relatif

L'âge relatif est défini par l'âge exact, par opposition à l'âge entier qui ne tient pas compte du jour et du mois de naissance [16]. Ainsi, au sein de la même catégorie d'âge, il peut y avoir jusqu'à 365 jours de différence entre deux athlètes. Cette différence d'âge peut également se traduire par des différences de taille, de poids, de force, d'expérience et d'agilité. Pour cette raison, les athlètes plus âgés dans la même catégorie d'âge peuvent être favorisés dans les sélections par rapport aux plus jeunes : c'est ce qu'on appelle l'effet de l'âge relatif [156]. Une étude met en évidence la surreprésentation des joueurs de rugby britanniques, avec 73 % nés au premier semestre de l'année par rapport à 27 % au second semestre [65]. D'autres sports collectifs exposent aussi un effet d'âge relatif dans les catégories jeunes : football [7], [16]–

[30], basketball [34], [44]–[56], handball [34], [47], [48], [58], [70]–[78] , rugby [57]–[69] , volleyball [31]–[43] et hockey sur glace. Cet effet d'âge relatif est également présent dans les sports individuels tels que la natation [104] ou l'athlétisme [334]. L'effet de l'âge relatif n'est plus à prouver et les études portent désormais sur l'atténuation et l'exclusion de ce biais [8].

Abandon

Le terme "abandon" désigne un individu qui a participé à un sport en particulier, puis a arrêté de participer à ce même sport sans pour autant arrêter définitivement de participer à d'autres sports [228]. Le retrait peut être décrit comme la résiliation intentionnelle ou obligatoire de la participation aux sports pour les jeunes [123]. Plusieurs raisons peuvent conduire au retrait : perte d'intérêt, ennui dans l'activité actuelle, intérêt pour une autre activité, conflit avec l'entraîneur, perte de plaisir, fréquence des blessures, stagnation des performances ou des compétences [123], [124]. En revanche, les athlètes qui persévèrent dans le même sport bénéficient généralement d'un plus grand soutien parental, et les récompenses qu'ils obtiennent de leur succès dans les compétitions créent un cercle vertueux en faveur de leur engagement [124], bien que trop de pression de la part des parents pendant l'adolescence puisse également conduire à la désaffection [125].

Maturation

La croissance et la maturation biologique sont deux processus cruciaux dans le développement du jeune athlète. D'une part, la croissance est définie par l'augmentation progressive de la dimension de certaines parties du corps ou de la totalité de celui-ci [161]. Durant cette période et avec l'âge, la taille et le poids augmentent et les organes deviennent plus importants également [161]. D'autre part, la maturation biologique est le processus qui mène à l'état de maturité [161]. Elle est définie de manière quantitative, en emmenant la fonction d'un organe ou un système biologique à son état de fonctionnement adulte [162]. Grâce à l'âge biologique, il est possible de situer de la maturation de l'adolescent. De nombreuses études mettent en relation les tests physiques et la maturation physique, en particulier dans les sports collectifs [17], [66], [261]–[264].

Spécialisation précoce

La spécialisation précoce est définie comme un entraînement intensif qui a lieu toute l'année dans un seul sport, excluant la pratique d'autres sports, chez des enfants prépubères [188]. « Précoce » ici, désigne les années avant l'adolescence. Sont soulignés les limites de la spécialisation précoce, car elle peut avoir à la fois des impacts physiques, avec des blessures répétées [191], et des impacts psychologiques, avec un risque d'abandon précoce [194]. Plusieurs raisons peuvent mener à l'abandon dans la littérature dont la spécialisation précoce que l'on oppose souvent à la diversification. En effet, pour éviter les blessures à répétition ou l'impact psychologique négatif menant au burnout, il est conseillé de pratiquer plusieurs disciplines favorisant le développement physiologique et psychologique de l'athlète.

OBJECTIFS

L'objectif de cette thèse consiste à améliorer les méthodes actuelles de détection qui sont trop focalisées sur les seules performances, qui plus est, réalisées à un instant T. Nous faisons l'hypothèse que chaque jeune athlète est doté d'un potentiel qui peut être masqué par différents paramètres, tels que les âges relatifs, biologiques. Ainsi, le but principal est de mesurer et de mettre en œuvre des méthodes pour prendre en compte les âges relatifs et biologiques dans les processus de détection et de sélection afin de tendre vers de l'estimation de potentiel.

METHODES

Sources de données

Deux bases de données sont utilisées pour répondre aux objectifs de cette thèse.

La première, transmise par la Fédération Française de Natation, rassemble toutes les données de performance des nageurs et nageuses depuis 2000. Dès qu'un nageur ou une nageuse participe à une compétition, quel que soit le niveau de la compétition (départemental, régional, nationale, continentale, mondial), son temps de performance ainsi que les autres informations relatives à cette course (nage, longueur de bassin, ville de compétition, phase finale ou non) sont récoltés et réunis. Toutes les épreuves sont concernées :

- Nage libre : 50m, 100m, 200m, 400m, 800m and 1500m

- Dos : 50m, 100m, 200m
- Brasse : 50m, 100m, 200m
- Papillon : 50m, 100m, 200m
- 4 nages : 100m, 200m and 400m.

La seconde base utilisée provient de la Fédération Française d’Athlétisme où l’équivalent existe depuis 2010 avec les épreuves suivantes :

- Sprints: 100m, 200m, 400m
- Haies: 400m, 110m for males and 100m for females
- Course de moyenne et longue distance : 800m, 1000m
- Sauts: pole vault, high jump, long jump, triple jump
- Lancers: shot put, hammer throw, javelin throw, discus throw.

Analyse statistique

5,339,351 performances des nageurs français âgés de 10 à 18 ans ont été collectées entre 2000 et 2019 en natation et 358,610 performances d’athlètes âgés de 12 à 21 ans de 2009 à 2019 en athlétisme. La répartition des trimestres de naissance a été examinée en fonction du niveau de compétitivité ('Tous', 'Top 50 %', 'Top 25 %' et 'Top 10 %'), de l'épreuve et de la catégorie d'âge. Une relation linéaire entre la répartition des performances et les jours du calendrier fournit un coefficient de calibration permettant de rééquilibrer les performances en tenant compte de l'effet de l'âge relatif pour chaque épreuve. Ensuite, les performances ajustées sont calculées en utilisant ce coefficient, la performance initiale et l'âge relatif. La validation est obtenue par le test statistique de Wilcoxon sur les données réelles des athlètes. Lorsque nous nous sommes intéressés à l’abandon en natation, des tests du chi deux ont été réalisés pour valider la significativité de l’effet du trimestre de naissance sur la performance. Des courbes de survie de Kaplan-Meier ont été établies pour déterminer et analyser l'impact du sexe et de l'âge relatif sur l'abandon. Quant à l’analyse autour de l’âge biologique des nageurs, le niveau de maturité de chaque nageur a été estimé grâce aux données de poids, taille assise et taille debout collectées sur les Championnats de France juniors de natation en 2022 [165]. Puis, ce niveau de maturité a été mis en lien avec les performances réalisées lors de cette compétition. Enfin, nous nous sommes intéressés à l’impact de la spécialisation précoce en compétition des

nageurs via des mesures de taux de conversion entre les catégories jeunes et la catégorie senior au niveau national et international.

RESULTATS

Effet de l'âge relatif

Les deux premières études mettent en lumière un effet d'âge relatif chez les nageurs et athlètes Français. La proportion de nageurs nés au premier trimestre est plus élevée que la proportion de ceux nés au dernier trimestre pour toutes les épreuves et tous les styles de nage ($p < 0,01$). L'effet de l'âge relatif augmente avec le niveau de compétitivité pour toutes les épreuves. En effet, parmi tous les nageurs de 12 ans en 50 mètres nage libre, la proportion née au premier trimestre est de 30,9 % contre 19,2 % au quatrième trimestre. Tandis que parmi les "Top 10 %", 47,5 % sont nés au premier trimestre contre 10,3 % au dernier trimestre (p -value $< 0,01$). En moyenne, chaque jour représente un écart de 0,008 seconde, ce qui se traduit par une différence de près de 3 secondes sur une année.

Quant à l'athlétisme, pour les filles de moins de 13 ans (U13), la proportion de sprinteuses sur 100 m sprint nées au quatrième trimestre (Q4) est de 21,4 %, 19,3 % et 16,2 % respectivement pour les catégories "Toutes", "Top 50 %" et "Top 10 %". De même, chez les garçons, la proportion de ceux nés au premier trimestre de l'année (Q1) augmente considérablement chez les moins de 14 ans (U14) : 27,6 %, 34,4 % et 43,4 % respectivement pour les catégories "Toutes", "Top 50 %" et "Top 10 %". Dans cette même épreuve, une différence d'un an entre les dates de naissance de deux athlètes représente un gain moyen de 931,01 ms (6,5 %) dans la catégorie U13 (moins de 13 ans) et de 229,65 ms (1,9 %) dans la catégorie U17 (moins de 17 ans). En comparant les performances rééquilibrées et les performances réalisées de chaque nageur et athlète, nous ne pouvons pas dire qu'elles sont significativement différentes. En moyenne, il n'y a pas de différence significative entre ces deux performances. Nos méthodes de rééquilibrage validées permettent de compenser les biais induits par l'effet de l'âge relatif. Cet outil est validé en comparant les nageurs et athlètes qui ont participé au moins deux fois au cours d'une saison. Il fournit une méthode de rééquilibrage jour après jour pour toutes les épreuves de natation et d'athlétisme et toutes les catégories d'âge.

Abandon

L'étude 3 porte sur les variables influençant l'abandon parmi le sexe, le trimestre de naissance et le niveau de performance. Parmi ceux qui ont au moins 21 ans et ont pratiqué pendant au moins deux saisons, 79,1 % des hommes et 87,2 % des femmes ont abandonné la natation. Indépendamment de l'âge auquel les performances sont réalisées, les filles abandonnent le plus souvent à l'âge de 13 ans et les garçons à l'âge de 17 ans. À l'âge de 13 ans dans le top 10%, 40,3 % des nageuses sont nées au premier trimestre de naissance contre 12,4 % au quatrième trimestre de naissance, tandis que 47,3 % des garçons sont nés au premier trimestre contre 8,7 % au quatrième trimestre de l'année. Dans le bottom 10%, 28,1 % des nageuses et 32,3 % des nageurs sont nés au quatrième trimestre contre 21,0 % et 17,3 % nés au premier trimestre de l'année respectivement. Pour les filles de 14 ans, 8,7 % abandonnent dans le top 10% contre 78,1 % dans le bottom 10%. De même, parmi les garçons de 14 ans, un taux d'abandon de 9,9 % a été observé dans le top 10% contre 69,3 % dans le bottom 10%. Des courbes de Kaplan Meier ont été utilisées pour étudier l'évolution du début de l'abandon en fonction du sexe et du trimestre de naissance. La plus grande différence observée entre les courbes correspondant au premier trimestre et dernier trimestre chez les filles se produit à l'âge de 12,71 ans avec une différence de 10 %. De plus, à l'âge de 14,67 ans, âge auquel la différence maximale est atteinte, les garçons nés au quatrième trimestre ont 8,1 % de chances en plus d'abandonner que ceux nés au premier trimestre.

Maturation

L'objectif de l'étude 4 consistait à mettre en lien la performance et le niveau de maturité parmi les participants aux Championnats de France Juniors de 2022. Cette étude met en avant que les meilleurs nageurs participent à davantage d'épreuves et sont plus matures que leurs homologues moins rapides. De manière équivalente, parmi les nageurs les moins performants, nous retrouvons une majorité de nageurs peu matures. Par conséquent, l'évaluation de la performance semble influencée par le niveau de maturité. Ces résultats soulignent l'importance de prendre en compte la maturation lors de l'évaluation des nageurs au sein de groupes d'âge spécifiques, dans le but d'apporter un soutien plus complet aux nageurs.

Spécialisation précoce

Afin de s'intéresser aux devenir des nageurs non seulement, au sein de leur épreuve mais aussi dans les compétitions internationales, nous avons observé le top 10%, qui représente les meilleurs nageurs Français. Nous notons des taux de conversion plutôt faibles dans certaines épreuves de longue distance féminines. Cependant, les taux de conversion les plus élevés sont observés de la catégorie junior à la catégorie senior. Nous remarquons que les taux de conversion les plus élevés concernent les épreuves masculines de 50m et 100m nage libre ainsi que 50m et 100m papillon. Nous avons également examiné les taux de conversion entre les juniors et seniors dans les compétitions internationales. Parmi les juniors qui ont participé aux Jeux Olympiques de la Jeunesse (JOJ), 13% ont atteint les Jeux Olympiques, 21% les Championnats du Monde senior, 13% les Championnats d'Europe senior et 52% n'ont participé à aucune de ces compétitions internationales. Lorsque nous nous intéressons aux Olympiens senior, 5% avaient atteint les JOJ, 19% les Championnats du Monde junior et 27% les Championnats d'Europe junior. En revanche, 49% n'avaient participé à aucune de ces compétitions internationales majeures en catégorie junior. Par conséquent, nous constatons donc qu'atteindre un très haut niveau dans les catégories jeunes n'est pas une condition nécessaire à la réussite en senior en natation.

CONTRIBUTIONS PRINCIPALES ET CONCLUSION

Les principales contributions de cette thèse sont les suivantes : 1) l'identification d'un effet d'âge relatif parmi les nageurs et athlètes Français, effet qui devient plus prononcé à mesure que le niveau de performance augmente ; 2) la proposition et validation d'une méthode de rééquilibrage qui permet d'évaluer de manière plus précise la performance de l'athlète en prenant en compte son âge exact ; 3) l'importance de considérer l'âge exact au travers des trimestres de naissance pour l'abandon ; 4) le lien fort entre niveau de maturité et performance ; 5) les taux de conversion faibles d'une catégorie à celle d'au-dessus démontrant la nécessité retravailler les critères et la définition de détection.

Les limites principales sont liées aux aspects suivants : malgré l'utilisation conséquente de l'équation de Mirwald dans la littérature afin d'estimer l'âge au pic pubertaire, celle-ci reste

très critiquable. Sa faible population d'étude qui est non sportive est peu similaire aux populations qui sont présentes dans nos bases de données. Ce qui peut fragiliser les estimations des niveaux de maturité des sportifs. Dans la littérature, il est aussi dit que plus on s'éloigne de l'âge au pic moins les estimations sont fiables. Or, notre échantillon d'étude n'était constitué que de nageurs juniors qui avaient pour presque la totalité d'entre eux déjà passé leur pic pubertaire. D'autre part, les régressions linéaires servant à calculer le coefficient de l'effet de l'âge relatif sont, contrairement aux autres méthodes de la littérature, faites par catégorie d'âge. Lorsque les autres auteurs effectuent une seule courbe d'approximation des performances, nous avons souhaité capturer par le biais des coefficients la puissance de l'effet de l'âge relatif au sein de chaque catégorie d'âge, indépendamment de celle qui précède ou celle qui suit. Enfin, on peut également noter que les deux sports présentés sont des sports métriques. Cela facilite grandement l'application des méthodes de rééquilibrage, l'utilisation des courbes de Kaplan Meier et l'analyse de performances. En revanche, cela s'avèrerait moins facile avec des sports collectifs ou artistiques.

La force de ce travail repose premièrement, sur des bases de données considérables. En effet, les analyses disposent d'une fiabilité forte étant donnée les millions de données qui sont traitées. D'autre part, ces travaux peuvent être transférés à d'autres sports, collectifs ou non métriques. En effet, en identifiant les variables déterminantes de la performance (tels que des tests physiques) pour chaque catégorie d'âge, il est envisageable d'appliquer les méthodes de rééquilibrage sur ces variables. À cet égard, l'ensemble de ces recherches visent à mettre en avant de nouvelles variables à prendre en considération, en s'éloignant de la sélection basée sur la performance et en se tournant vers l'estimation du potentiel chez le jeune athlète. De plus, avec un aspect plus applicatif, ce travail vise à sensibiliser les professionnels du sport aux problèmes cachés posés par la sélection basée sur la performance actuelle. En appréciant mieux les données individuelles, il est alors envisageable d'améliorer les techniques actuelles de détection.

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APPENDICES



Relative Age Effect Among French Swimmers

Audrey Difernand^{1,2}, Quentin De Larochelambert^{1,2}, Robin Pla^{2,3}, Juliana Antero^{1,2}, Jean-François Toussaint^{1,2,4}, Adrien Sedeaud^{1,2}

¹Institute for Research in Medicine and Epidemiology of Sports (IRMES – URP 7329), University of Paris Cité, Paris, France. ²National Institute of Sports, Expertise and Performance (INSEP), Paris, France. ³French Swimming Federation, Paris, France. ⁴CIMS, AP-HP, Hôtel-Dieu, Paris, France



Context

Relative age is defined by the exact age as a precision of the integer age which does not consider the day and month of birth¹. Thus, within the same age category, there can be up to 365 days difference between two athletes. This age difference can also be translated into differences in height, weight, strength, experience and agility. For this reason, older athletes within the same age group may be favored in selections compared to younger ones: this is called relative age effect (RAE)². The RAE has been shown for both sexes³ and in multiple sports like ice hockey, football, volley-ball, basket-ball, baseball, rugby, tennis, track-and-field⁴ and swimming⁵. This phenomenon can have several consequences. The older, taller, bigger and more experienced athletes have a non negligible advantage⁶ as selections are based on current performances⁶. Also, the motivation of younger athletes is negatively impacted⁷.

References : ¹Helsen & al, 1998, ²Musch & al, 2001, ³Smith & al, 2018, ⁴Cobleby & al, 2009, ⁵Costa & al, 2013, ⁶Post & al, 2020, ⁷Delorme & al, 2010

Objectives

- 1- To test the presence of RAE in all individual swimming events and performance levels
- 2- To determine and apply corrective adjustment procedures for all disciplines and age categories
- 3- To rebalance individual performances

Data

- 62 610 swimmers between the ages of 10 and 16
- 100m Male Freestyle in Olympic pool
- Competition between 2000 and 2020
- All performances from local to international level were collected by the French Swimming Federation
- Date of birth, date of competition

Methods

1- Birth quarters distribution

In the first part, we kept only the season best performance for each swimmer. Swimmers were divided into birth quarters (Q1: January, February, March, Q2: April, May, June, Q3: July, August, September, Q4: October, November, December). To test for a significant difference between the birth quarters, chi-square test, odds ratios and 95% confidence intervals were calculated.

2- Corrective adjustment procedures

To better visualize the differences between swimmers, we defined the relative age gap. It is the time between the last birthday and the competition date. Within each age category, we used the relative age gap and performance in order to reveal the nature of the relationship between these two variables. Then, using the regression coefficient, we calculated the rebalanced performance, where:

$$T_r = T_0 - c * m$$

T_r: rebalanced performance time, T₀: initial performance time, c: slope coefficient, m: time until the next birthday

3- Validation

In the second part, in order to validate our rebalancing method, we used a database composed of swimmers having achieved 2 performances in the season with a minimum of 6 months difference. The rebalancing method is applied to the first performance considering the difference with the second performance. where:

$$T_r = T_1 - c * (T_2 - T_1)$$

T_r: rebalanced performance time, T₁: initial performance time, T₂: second performance time, c: slope coefficient

Thus, it has been possible to compare the rebalanced performance with the second performance achieved with significance tests (Friedman test and Wilcoxon test).

Age	Top %	Total	Q1 (%)	Q2 (%)	Q3 (%)	Q4 (%)	χ²	p-value	OR	p	95% CI
10	100	3767	897 (23.81)	871 (23.12)	1087 (28.86)	912 (24.21)	30.78	***	0.98	**	[0.97 ; 0.99]
11	100	6982	1706 (24.43)	1738 (24.89)	1941 (27.8)	1597 (22.87)	35.46	***	1.09	**	[1.06 ; 1.12]
12	100	9807	2661 (27.13)	2498 (25.47)	2554 (26.04)	2094 (21.35)	75.20	***	1.37	**	[1.28 ; 1.47]
13	100	12787	3655 (28.58)	3426 (26.79)	3152 (24.65)	2554 (19.97)	211.99	***	1.60	**	[1.5 ; 1.7]
14	100	15140	4559 (30.11)	4147 (27.39)	3540 (23.38)	2894 (19.11)	418.50	***	1.82	**	[1.72 ; 1.93]
15	100	14127	4547 (32.19)	3976 (28.14)	3034 (21.48)	2570 (18.19)	679.78	***	2.13	**	[2.01 ; 2.25]
10	10	376	48 (12.77)	92 (24.47)	134 (35.64)	102 (27.13)	40.26	***	0.39	**	[0.29 ; 0.52]
11	10	698	91 (13.04)	179 (25.64)	267 (38.25)	161 (23.07)	90.15	***	0.50	**	[0.43 ; 0.58]
12	10	980	156 (15.92)	262 (26.73)	365 (37.24)	197 (20.1)	101.69	***	0.75	**	[0.71 ; 0.79]
13	10	1278	281 (21.99)	386 (30.2)	381 (29.81)	230 (18.0)	55.39	***	1.28	**	[1.2 ; 1.37]
14	10	1514	428 (28.27)	450 (29.72)	392 (25.89)	244 (16.12)	68.26	***	2.05	**	[1.73 ; 2.43]
15	10	1412	426 (30.17)	416 (29.46)	342 (24.22)	228 (16.15)	70.95	***	2.24	**	[1.86 ; 2.7]

Table 1: Distribution by birth quarters with respect to age groups and level of competitiveness

Conclusion and Discussion :

- First study to demonstrate the relative age effect among French swimmers, particularly among males' 100m Freestyle in 50m pools.
- RAE increases when the level of competitiveness increases.
- Thanks to the rebalancing method, it is possible to objectify swimmers' performances in relation to their exact age in order to better appreciate their potential and improve talent identification processes.
- To go further, other variables as maturity could be included and improve the method.

Audrey Difernand - audrey.difernand@insep.fr

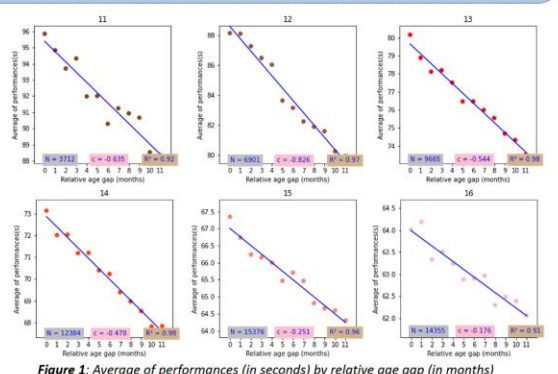


Figure 1: Average of performances (in seconds) by relative age gap (in months)

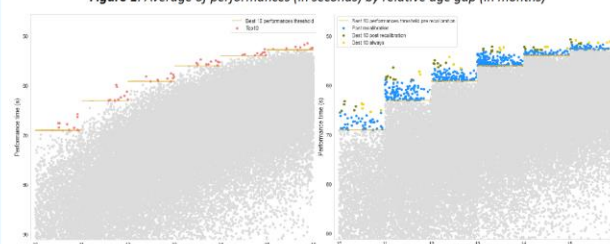


Figure 2: Pre-rebalanced performances VS Post-rebalanced performances

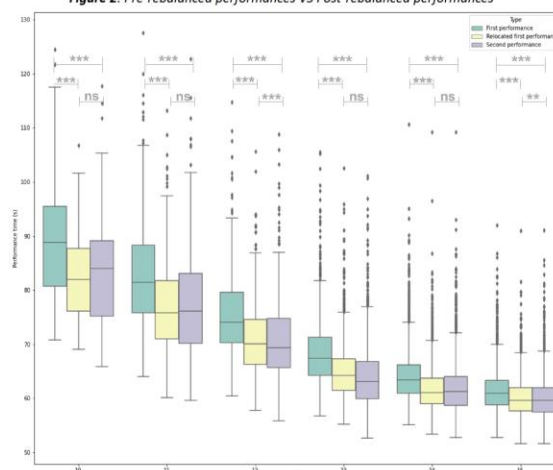


Figure 3: Boxplots of first, rebalanced and second performances by age



Dropout among French swimmers: gender, relative age effect and performance level influences



Audrey Difernand^{1,2}, Alexia Mallet^{1,2}, Quentin De Larochelambert^{1,2}, Nathan Miguens^{1,2}, Robin Pla^{2,3}, Juliana Antero^{1,2}, Jean-François Toussaint^{1,2,4}, Adrien Sedeaud^{1,2}

¹Institute for Research in Medicine and Epidemiology of Sports (IRMES – URP 7329), University of Paris Cité, Paris, France. ²National Institute of Sports, Expertise and Performance (INSEP), Paris, France. ³French Swimming Federation, Paris, France. ⁴CIMS, AP-HP, Hôtel-Dieu, Paris, France



Context

Dropout is defined as someone who participated in a particular sport and then stopped participating in that same sport but did not permanently stop participating in any other sport¹. **Youth withdrawal** may be described as the intentional or mandatory termination of participation in youth sports². Several reasons can lead to withdrawal²⁻³: **loss of interest, boredom in the current activity, interest in another activity, conflict with the coach, loss of pleasure, frequency of injuries, stagnation of performance or skills**. In contrast, athletes who persist in the same sport usually enjoy greater parental support, and the rewards they obtain from their success in competitions create a virtuous circle in favor of commitment³, though **too much pressure** from parents during adolescence may also lead to disengagement⁴.

References : ¹Moulds & al, 2020, ²Rottensteiner & al, 2013, ³Brown & al, 1985, ⁴Monteiro & al, 2017

Objective

Investigate the evolution of the dropout rate with respect to sex, level of performance and birth quarters among French male and female Freestyle short-distance swimmers.

Data

- 160 861 swimmers (49.2% males)
- All individual non-combined events (50m, 100m, 200m, 400m, 800m, 1500m Freestyle, 50m, 100m, 200m Breaststroke, Backstroke and Butterfly)
- Competitions between 2000 and 2020
- Birthdate, performance time, competition and pool length

Methods

Relative age effect

The distribution of the birth quarters (Q1: January-March, Q2: April-June, Q3: July-September, Q4: October-December) was calculated for each performance decile.

Dropout

Dropout in this section will be defined as a swimmer disappearing from the database before the age of 21 (as we look at youth dropout) or as the absence for at least two seasons of swimmers not yet 21 years old at the last recorded competition. We measure the dropout proportion for each performance decile, event and sex.

Survival analysis

To study the evolution of the onset of dropout according to sex and birth quarter, Kaplan Meyer Survival (KMS) curves were estimated. In this study, KMS curves were plotted according to relative age in order to compare athletes at a similar stage of their career. Kaplan Meier estimates were computed to determine differences in terms of dropout between birth quarter for each sex. To assess the significance of the results, log-rank tests were performed for each considered groups.

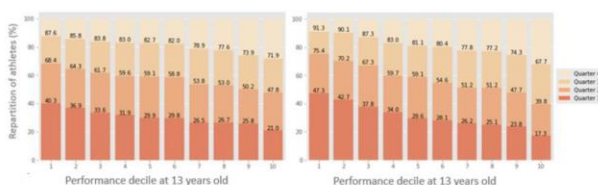


Figure 1: Distribution by birth quarter and performance decile of swimmers at 13 years old in the female (left) and male (right) 50m Freestyle competing in the 50m Olympic swimming pools

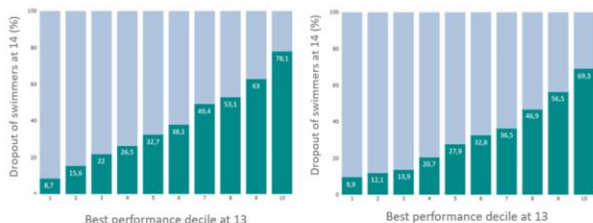


Figure 2: Dropout rate at age 14 based on performance deciles at age 13 in the female (left) and male (right) 50m Freestyle in the 50m Olympic swimming pool.

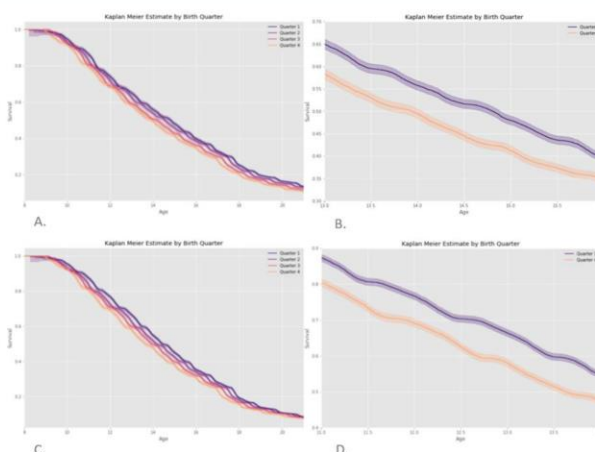


Figure 3: (A) KMS curves according to birth quarters for males (B) Zoom in on the first and last quarter KMS for males between 13 and 16 years of age (C) KMS curves according to birth quarters for females (D) Zoom in on the first and last quarter KMS for females between 11 and 14 years of age

Results

Among those who are at least 21 years old and have been practicing for at least two seasons, 79.1% of male and 87.2% of female have dropped out of swimming. Regardless of the age at which the performances are carried out, girls drop out the most at 13 and boys at 17. When we look at the ratio of these frequencies to the population of the age concerned, the dropout rate is higher at 17 for both girls and boys.

At age 13 in decile 1, 40.3% of female swimmers are born in Q1 vs. 12.4% in Q4 (Figure 1 left), while 47.3% of males are born in Q1 vs. 8.7% in Q4 (Figure 1 right). In decile 10, 28.1% of female (Figure 1 left) and 32.3% of male swimmers (Figure 1 right) were born in Q4 vs. 21.0% and 17.3% born in Q1 respectively.

For the 14-year-old girls, 8.7% drop out in decile 1 vs. 78.1% in decile 10 (Figure 2 left). Similarly, among 14-year-old boys, a dropout rate of 9.9% was observed in decile 1 vs 69.3% in decile 10 (Figure 2 right).

The largest observed difference between the two corresponding KMS curves among girls occurs at 12.71 years old with a 10% difference (Figure 3D). In addition, at 14.67 years old, age at which the maximum difference is reached, male born in the fourth quarter are 8.1% more likely to drop out than those born in the first quarter (Figure 3B).

Conclusion and Discussion

This study highlights the impact of sex, birth quarter and performance level on dropout rate. It shows that the dropout rate increases when the level of performance decreases. The Kaplan Meier survival curves show a similar evolution of dropout rates for girls and boys until the age of 13, after which girls tend to drop out significantly more than boys, who face a peak in dropout around the age of 17.

audrey.difernand@insep.fr



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Quentin De Larochelambert, Audrey Difernand, Juliana Antero, Adrien Sedeaud, Jean-François Toussaint, Louis Pierre Yves & Nicolas Coulmy

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Relative age effect in French alpine skiing: Problem and solution

Quentin De Laroche Lambert^{a,b,c}, Audrey Difermand^{c,d}, Juliana Antero^c, Adrien Sedeaud^c, Jean-François Toussaint^{c,d,e}, Louis Pierre Yves^{a,f} and Nicolas Coulmy^b

^aInstitut de Mathématiques de Bourgogne, UMR 5584 CNRS, Université Bourgogne Franche-Comté, Dijon, France; ^bDépartement Scientifique et Sportif, Fédération Française de Ski, Annecy, France; ^cInstitut de Recherche bioMédicale et d'Epidémiologie du Sport, EA7329, INSEP, Université de Paris, Paris, France; ^dUniversité de Paris, France; ^eCentre d'Investigation en Médecine du Sport, Hôtel-Dieu, Assistance Publique, Hôpitaux de Paris, Paris, France; ^fInstitut Agro Dijon, PAM UMR 02.102, Université Bourgogne Franche-Comté, Dijon, France

ABSTRACT

This study aims to identify the potential bias of the relative age effect (RAE) in French alpine skiers and to propose a mathematical correction adjustment for such a bias. All performances and birthdates of skiers on the national and international circuit were collected from the 2004 up to 2019. A goodness-of-fit chi-square test and the residuals were used to study the distribution of birth trimesters in youth competitors. A linear relationship between the distribution of performances and the months obtains a calibration coefficient allowing to rebalance the performance by considering the effect of RAE. Individuals born at the beginning of the year are over-represented in the elite young selections in all disciplines for both genders. A coefficient based on the relationship between month of birth and performance adjusts individual performance and cancels out the effect of RAE. The results show that RAE is present in French alpine skiing. We present a method allowing to consider the effect of the RAE in the performances realized in each gender and discipline. This method allows coaches to have a more objective opinion on performance and to reduce selection bias.

ARTICLE HISTORY

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KEYWORDS

Ski; relative age effect; performance; maturity; talent identification

Introduction

The relative age effect is defined as a bias that advantage individuals born close to the age-group cut-off in the cohort entry (e.g. school tests, sports competitions; Helsen et al., 2005). The relative age effect has been a subject studied in many fields including education since Freyman (Freyman, 1965) and Armstrong (Armstrong, 1966) in the 1960s. The tendency of better success of the individuals born at the beginning of the year in the school environment has been confirmed in other studies. For example, Aune et al. showed a relative age effect in the Norwegian numeracy test for 5th, 8th, and 9th graders, an effect more remarkable among boys than girls (Aune et al., 2018). Copley et al. (S. Copley et al., 2009) studied the relative age effect in 657 pupils (aged 11–14) at a secondary school in North England. He found that older children (born in the first two trimesters) were more represented in gifted and talented programmes.

In sports, a 2018 study on the talent selection in 70 different sports, concerning 18,859 young Swiss athletes showed a moderate effect of relative age in athletics and synchronized swimming, as well as a slight effect but significant in tennis, volleyball, football and alpine skiing among girls (Romann et al., 2018). The RAE has been shown for both genders in young American football players (Rhys et al., 2018), rugby and cricket (McCarthy et al., 2016) and potentiated with the level of performance (Leyhr et al., 2021). Finally, Raschner et al. showed a relative age effect for both girls and boys at the 2012 Winter

Youth Olympic Games across all disciplines investigated (Raschner et al., 2012). Individuals who won medals were relatively older than their non-medallist counterparts. This bias results from an earlier maturity with higher performances for those born in the first months of a same year, the classification by age group favouring the performance of relatively older athletes (W. F. Helsen et al., 2000).

Maturity is defined as the stage in which an organism is found which has reached its full development. Regarding performance, we will talk about the development of physical, physiological or cognitive faculties. This link between development and performance has been studied and theorized (G. Berthelot et al., 2012; Geoffroy Berthelot et al., 2019; Moore, 1975) by a bi-phasic function of progression and decline. Depending on the determinants of sports performance, this maturity can be achieved at different ages. For example, maturity in chess, with a cognitive dominance, is reached at the age of 31, while in 100-m athletics, with a physical dominance, is reached at the age of 25. The determinants of performance vary depending on the sport and therefore also the phases of development and therefore the effects of RAE (Till et al., 2014).

This relative age effect generates long-term effects. Brustio et al. looked at the RAE to adulthood in world athletics (Brustio et al., 2019). They first of all confirmed the presence of bias in all disciplines in the youth categories (under 18 and under 20). They also identified a relative age effect that persisted into adulthood in some

CONTACT Quentin De Laroche Lambert  qdelarochelambert@ffs.fr  Institut de Mathématiques de Bourgogne, UMR 5584 CNRS, Université Bourgogne Franche-Comté, Fédération Française de Ski, Institut de Recherche bioMédicale et d'Epidémiologie du Sport, EA7329, INSEP, Université de Paris, Département Scientifique et Sportif, 21000 Dijon, Annecy, Paris, France.

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Figure 1. Distribution of proportions of female and male skiers according to their trimester of birth in French elite youth skiing competitions (U14 FFS, U16 FFS, U16 FIS). The stars indicate the level of significance level of the over or under representation of the corresponding trimester (*:0.05; **:0.01; ***:0.001).

disciplines, notably throwing events. Likewise, Gennaro Boccia et al have shown that being relatively born earlier in the year can confer an advantage throughout men's careers in throwing events (Boccia et al., 2021). Conversely, McCarthy et al. showed a reversal of the RAE advantage (McCarthy et al., 2016). Although relatively young professional rugby and cricketer players were less likely to be selected into their respective national academy systems, they were more likely to advance to senior national teams. McCarthy and Collins (McCarthy & Collins, 2014) confirm this "reversal" of the RAE in rugby. This reversal effect has been called the "underdog" effect (Gibbs et al., 2012). Finally, de la Rubia et al. showed a relative age effect still present in the adult male and female categories in international handball (De la Rubia et al., 2021).

Other studies have demonstrated the existence of the RAE among international skiers (Baker et al., 2014). Analyses of 1,474 ski jumpers, 7,501 cross-country skiers, 15,565 alpine skiers, 4,179 snowboarders and 713 Nordic

combined athletes revealed significant RAE for most of these disciplines for all genders. But no published study has investigated French alpine skiing. Since each country has its own system of talent identification, previous studies may not be simply extrapolated to the French spine skiing system. The presence of RAE in skiing was global and having not changed over the past 10–15 years (Steidl-Müller et al., 2019), it is useful to focus on this phenomenon in French alpine skiing specifically. In addition, no solutions regarding the RAE in alpine skiing has been proposed.

In other sports, solutions have been proposed to consider the RAE. In the National Hockey League, reducing the age groups; changing the annual limits for age groups; or to delaying the selection and identification processes beyond the stages of puberty and maturation have been tested (Barnsley & Thompson, 1985). Nolan and Howell have shown that these biases have persisted in hockey despite the available option for adjusting this bias (Nolan & Howell, 2010). Another study in basketball (De la Rubia Riaz et al.,

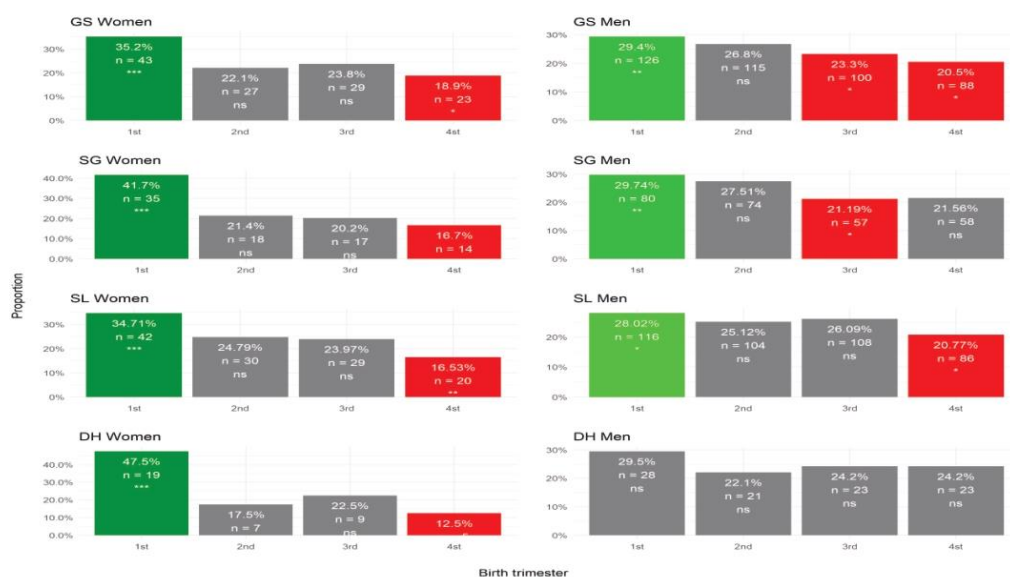


Figure 2. Distribution of the birth trimester of participants in international competitions (FIS) in the senior category (U30). The stars indicate the level of significance level of the over or under representation of the corresponding trimester (*:0.1; **:0.05; ***:0.01).

2020) proposed to evaluate the athlete on her/his performance in the long-term and not the immediate results only. They suggested to take into account the maturation of the athlete rather than the age groups and to design models of evaluation of young athletes accounting for other parameters (psychology, emotional intelligence, cognitive skills, etc.). These methods include development parameters linked to maturation, but none has presently been validated that would more precisely detect future talent. Romann and Cobley proposed a linear correction in sprint athletics (Romann et al., 2015). They showed that a relative age difference of nearly 1 year resulted in expected average performance differences ranging from of 10.1% to 5.3% among Swiss junior sprinters. Other corrective adjustment procedures were constructed from the regressed relationship between chronological age and objective performance measures of swimming (Abbott et al., 2020; Shaun et al., 2021; Stephen Cobley et al., 2019). A practical solution proposed by Helsen et al. in soccer (Helsen et al., 2021) makes it possible, based on a longitudinal study examining secular changes in biological maturation in Belgian boys, to determine an appropriate developmental allocation date by knowing the anthropometric characteristics of the individual. Its new classification based on this allocation date and not its chronological date, makes it possible to cancel the RAE.

A systematic review (Webdale et al., 2020) identified 10 independent solutions to RAE types from 63 peer-reviewed publications between 1980 and 2018. Six of these solutions were "technical and policy-based". This relates to modifying

the age structures, correcting performance by a coefficient, achieving player quotas and making categories by anthropometric parameters. Three proposed solutions were pedagogical and informational focusing above all on pedagogical training to raise awareness of the RAE bias. They highlight the difficulty of applying the different methods proposed and that the implementation of these solutions has the potential to affect both positively and negatively the career and life outcomes of participants. The recommended solutions seem difficult to implement quickly because they require substantial changes in sports organizations.

Therefore, we aimed to (1) determine the relative age effect in French alpine skiers in young age groups and adulthood and (2) recommend a method to consider the RAE. We hypothesized that a relative age effect is present in both genders among French alpine skiers and that a proper regression method could provide a robust solution to compensate for this effect.

Methods

Studied population

Inclusion criteria

The population studied included all male and female French alpine skiers having participated in at least one competition in Giant Slalom (GS), Slalom (SL) and Super Giant Slalom (SG) between the age of 13 up to 30 from the 2004/2005 season up to the 2018/2019 season.

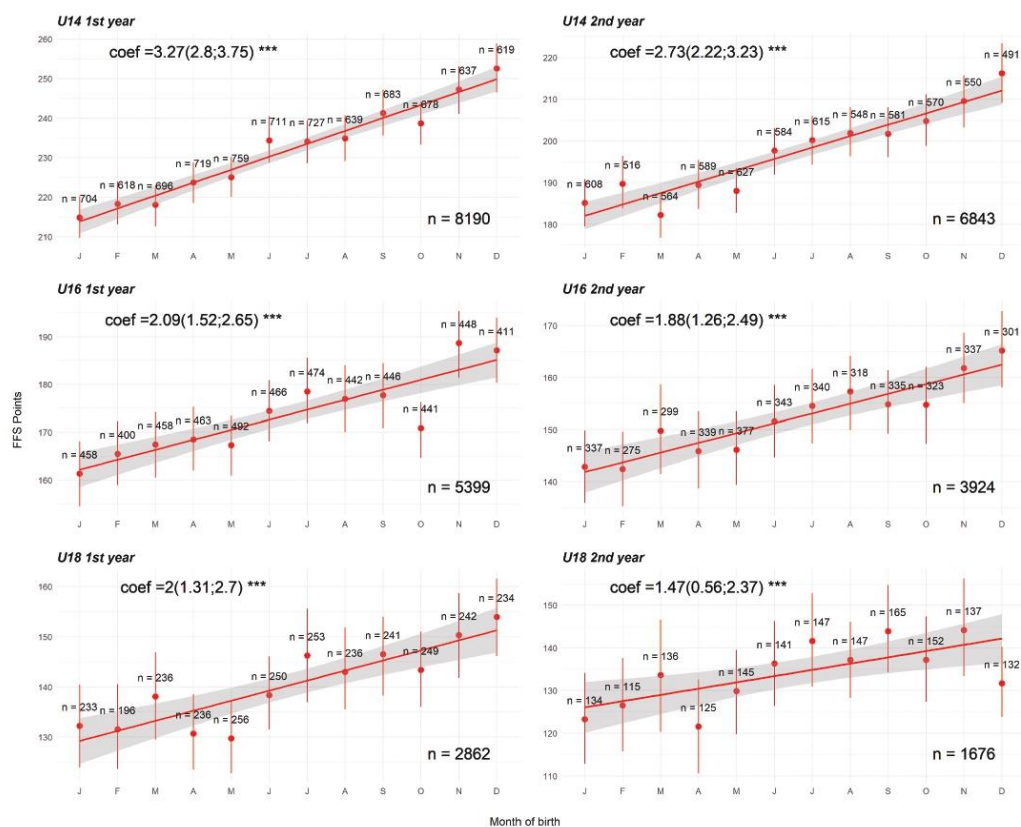


Figure 3. Performance (FFS points) according to the month of birth and calibration coefficient (coeff) at each age in male Giant Slalom.

Exclusion criteria

Downhill (DH) performances have been included for adult categories only (DH is not a discipline practiced in youth categories).

Sample description

The studied population consisted of 21,348 individuals, 7672 women (36%) and 13,661 men (64%). Among these competitors, 2793, 1917, 1162 individuals participated to the national U14, national U16 championship and international U18 championship, respectively. The distribution of performance and age for each category and gender are presented in the table.

Data source

The performance data on the national and international circuit as well as dates of birth were available on the website of the French Ski Federation: <http://www.ffs.fr/ski-alpin/competitions/resultats>. Alpine skiing performance is quantified using FFS (French Ski Federation) points. The number of points scored

on the day of the competition depends on the overall level of the race and the time achieved in relation to the winner of the race: $(\frac{T_x}{T_0} - 1) \cdot F$, with T_x the runner's time in seconds, T_0 the winner's time in seconds and F a discipline-dependent factor. The data regarding participation in elite youth competitions are private internal data that of the French Ski Federation made available for this study.

Data analysis

The age group categories in alpine skiing are determined according to the skiers' year of birth. The U14 category is made up of skiers born in year $y - 14$ and $y - 13$ for the season $y - 1/y$. The U16 category is made up of skiers born in year $y - 16$ and $y - 15$ and category U18 is made up of skiers born in year $y - 18$ and $y - 17$. For example, a skier born in 2006 will be in the U14 category for the 2018–2019 season. An individual can be present in several categories if he has competed for several years. For every year, there are two French (FFS) youth elite championships in U14 and U16 categories and

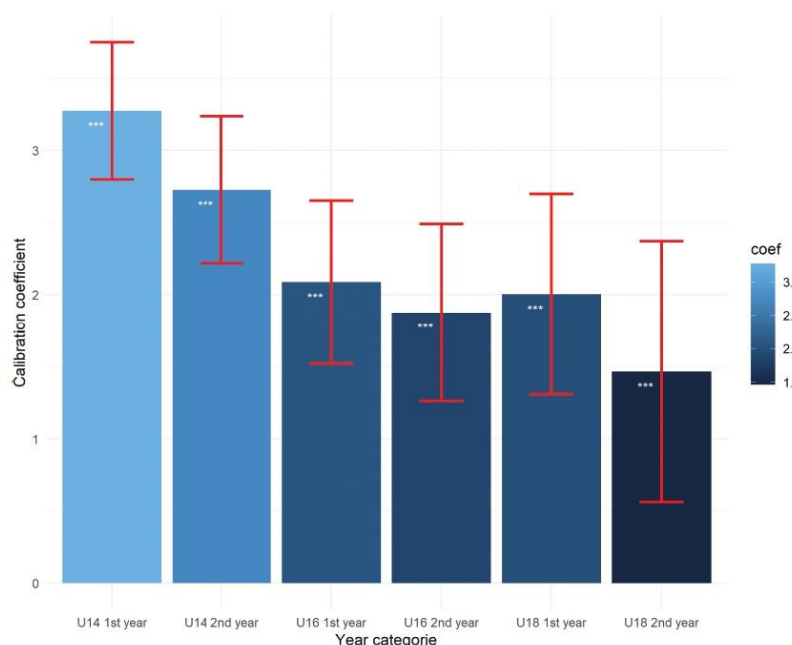


Figure 4. Calibration coefficient at each age in male Giant Slalom. The lighter the colour, the higher the coefficient and the higher the relationship between month of birth and performance. The 95% confidence interval of the coefficients is delimited by the errors bar.

one youth elite international (FIS: International Ski Federation) championships in U16 category. Only skiers selected by their regional committees in each category (U14, U16) participated in these competitions.

Identifying the relative age effect

To have a large sample size in each group and a higher statistical power, birth dates of participants in the elite young competitions (U14 and U16 FFS, U16 FIS) were categorized into trimesters (*January, February, March: Q1, April, May, June: Q2, July, August, September: Q3, October, November, December: Q4*). A chi-squared test of adequacy was used to compare the distribution of birth trimesters with the distribution of birth trimesters for the entire French population over the study period. Historical public data for the entire French population were obtained from the INSEE (Institut national de la statistique et des études économiques): <https://www.insee.fr/fr/statistiques/serie/000436391>. In the presence of a global effect, Haberman residuals (Haberman, 1973) were calculated and compared to the quantiles of the normal distribution (of order 0.1, 0.05, 0.01) to determine the birth trimester over or under represented. These residuals represent the standardized deviation between the observed and expected values. They asymptotically follow a standard normal distribution.

In the absence of a relative effect of age, the distribution of trimesters of birth is assumed to follow the distribution of the general French population, therefore a rejection of the null hypothesis of homogeneity will identify a relative age effect.

Relative age effect in adulthood

The homogeneity test was performed on the birth trimesters of individuals present on the international circuit (FIS) in adulthood (between 22 and 30 years) in GS, SG, SL and DH. The FIS circuit is the highest level of alpine skiing in the world. If the distribution of birth trimesters does not follow the French distribution, the relative age effect is present in adulthood.

Relocation RAE solution

The method was developed for the U14, U16 and U18 categories, individuals of the same category were separated by their year of birth y (first year) and $y + 1$ (second year). Each skier is represented only once per season, characterized by his best performance achieved. For each year, the dates of birth have been categorized into months of birth (January to December). At each age, a linear regression was performed between the month of birth and the skier best performance (in FFS points). If the slope coefficient a is significantly different

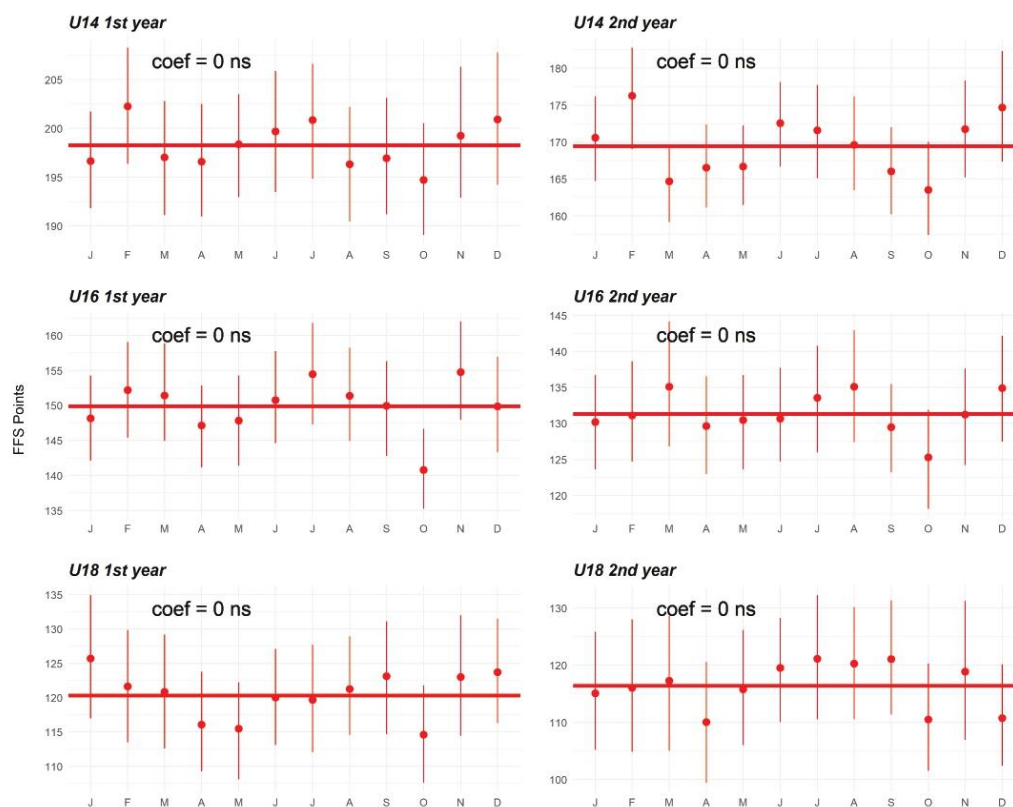


Figure 5. Performance (FFS points) according to the month of birth and calibration coefficient at each age in male Giant Slalom after performance correction.

from 0, it is used as a calibration coefficient to rebalance the effect of relative age. We calculated the “adjusted” points for each individual:

$$Pts_{corr}^j = Pts_j - \alpha_j * k$$

with: j : age, k : Birthtrimester

These adjusted points allow to compare several skiers independently of their month of birth. The categories being composed in 12-month range, the coefficients will adjust the performance within each of the group (1st and 2nd year). For example, the U14 1st year and the U14 2nd year will have two distinct coefficients, and will allow each individual to be compared with regard to his category (1st or 2nd year). We used a cross-validation method to check the robustness of our method. We cut our sample into two parts, one accounting randomly for 75% of the sample data, and another part with 25%. The 75% made it possible to calculate the calibration coefficients at each age category. Then, the calibration coefficients were then applied on the remaining 25% data sample. The RAE bias is

considered to be annulated cancelled out if the previous positive linear relationship between performance and month of birth on this “test” sample was now absent.

Results

Identifying the relative age effect

The birth trimesters of participants in elite youth competitions does not follow the distribution of the entire French population (proportion (%) = 24.4, 25.0, 26.1 24.4; Figure 1; $p < 0.05$). A relative age effect was identified in all youth competitions for both genders. Skiers born in the first trimester are over-represented in all categories (proportion (%) = 33.3, 31.7, 34.6, 27.1, 30.7, 29.2 for men’s U14; women’s 14; men’s U16; women’s U16; men’s U18 and women’s U18, respectively, $p < 0.01$). Skiers born at last trimester are underrepresented (proportion (%) = 16.7, 17.3, 15.8, 18, 16.6, 18.6 for men’s U14; women’s 14; men’s U16; women’s U16; men’s U18 and women’s U18, respectively, $p < 0.01$)

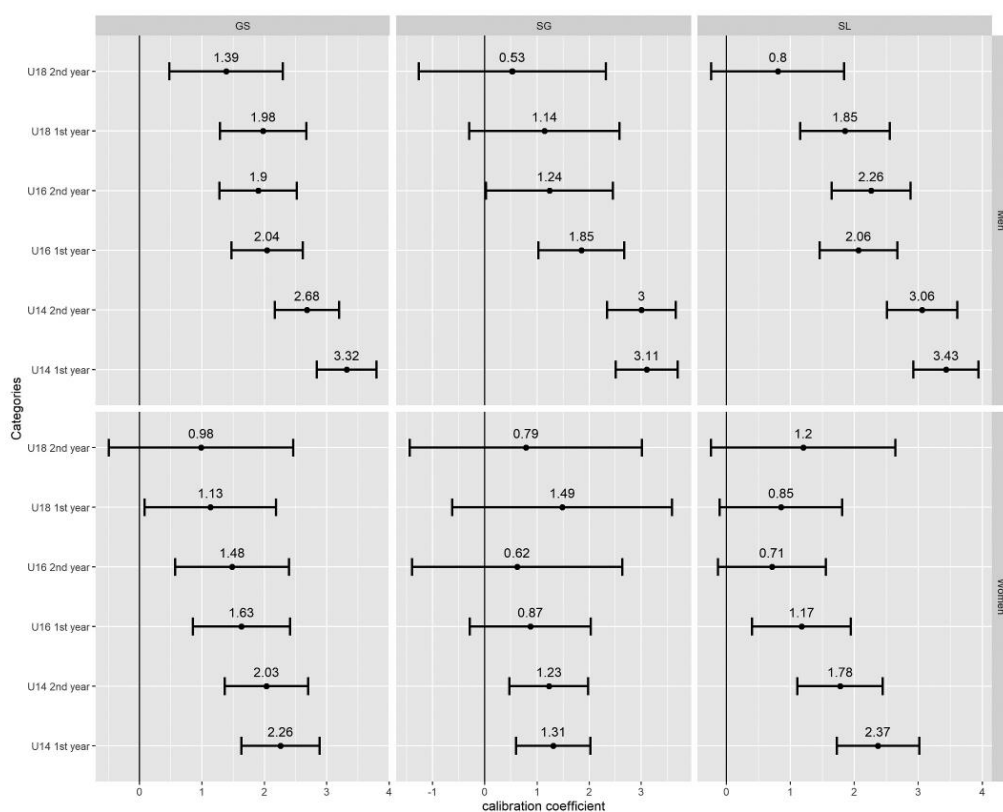


Figure 6. Calibration coefficient for all categories (in column) and for each gender (in line) in each category year. The horizontal axis is the calibration coefficient and the vertical axis is the year category. If the confidence interval (determined by the two horizontal bars) includes the value 0, the coefficient is not significantly different from 0.

The proportion observed in each discipline (GS, SG and SL) are represented in the Supplementary figures (Figure 7, 8, 9). A different distribution of the French population is present in all disciplines (GS, SG and SL) for national competitions (FFS). The first and second trimesters are overrepresented and the 3rd and 4th trimesters are underrepresented in all men's and women's disciplines for U14 competitions. In U16, the 4th trimester is underrepresented in all disciplines for both genders, and the first trimester is overrepresented in SG and SL.

Relative age effect in adulthood

Figure 2 shows an imbalance in the distribution of the birth trimesters among adult skiers as well compared to the French population. Individuals born in the first trimester are overrepresented in men GS (proportion = 29.4% $p < 0.05$), GS female (35.2% $p < 0.01$), SG male (proportion = 29.7% $p < 0.05$), SG female (proportion = 41.7% $p < 0.01$), SL male (proportion = 28% $p < 0.1$), SL female (proportion = 34.7% $p < 0.01$) and DH women (proportion = 47.5% $p < 0.01$).

Individuals from the last trimester are underrepresented in GS male (proportion = 20.5% $p < 0.1$), GS female (proportion = 18.9% $p < 0.1$), SG female (proportion = 16.7% $p < 0.1$), SL male (proportion = 20.8% $p < 0.1$), SL female (proportion = 16.5% $p < 0.1$) and DH women (proportion = 12.5% $p < 0.1$).

Relocation RAE solution

The methodology allowing performance to be adjusted by the relative age effect developed in all categories for both genders in alpine skiing is presented for the densest category in terms of the number of performances achieved, the male GS. A linear relationship between performance and month of birth for each category in Giant Slalom is illustrated in Figure 3. In each age category, the slope coefficient is different from 0 (3.27, 2.73, 2.09, 1.88, 2, 1.47 for men's U14 1st and 2nd year; women's U14 1st and 2nd year; men's U16 1st and 2nd year; women's U16 1st and 2nd year; men's U18 1st and 2nd year and women's U18 1st

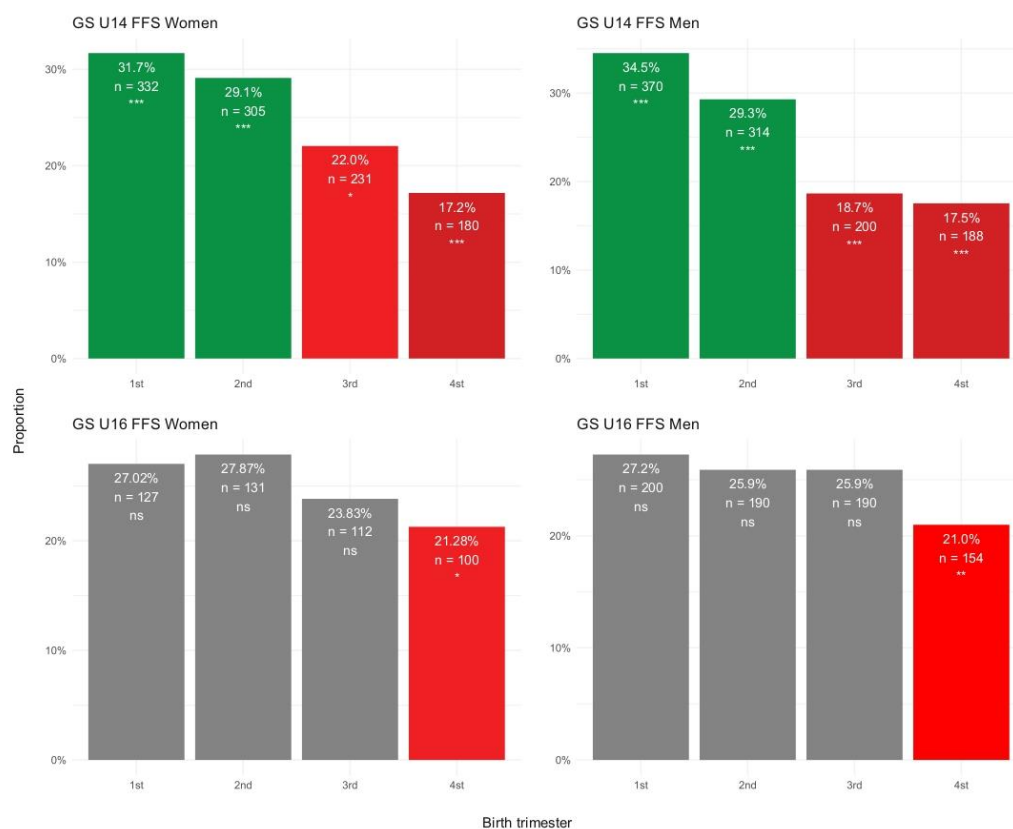


Figure 7. Distribution of terms of birth by category for elite youth competitions (FFS U14 above and FFS U16 below) and each gender (male on the right and female on the left) in GS.

and 2nd year). This coefficient represents the potential gain in points for each additional birth month at each age in male GS. Calibration coefficients as well as the confidence intervals are summarized in Figure 4 for each category, gender and discipline.

After correcting the performance/age relationship using the calibration coefficient, the RAE was considered in Figure 5 (\forall age: $\alpha_{age} = 0$, $p > 0.05$). All the confidence intervals of the performance averages for each month of birth follow the linear trend with a zero slope, except for the month of October for the U16 first year category.

Figure 6 also includes the calibration coefficients obtained with the methodology presented for women (bottom) also and for the disciplines SG, GS and SL (in column). For each category (on the vertical axis) is represented the calibration coefficient as well as its confidence interval delimited by the two bars. If the value 0 (represented by the horizontal bar) is within the confidence interval, the assumption that the calibration coefficient is equal to 0 is not rejected. A null calibration coefficient means that the month of birth has no influence on performance. All

the calibration coefficients for the U14 categories (1st and 2nd year) are significantly different from 0. Conversely, four coefficients are significantly different from 0 in U18 1st year and 1 in U18 2nd year.

Discussion

This study shows the relative age effect in all disciplines and age categories among French alpine skiers. It also demonstrates that this effect lasts until adulthood in the international FIS circuit, with a higher proportion of individuals born at the beginning of each year. Based on such findings, we propose a solution to adjust for this effect via a calibration coefficient calculated for each event, age category, and gender. This option allows coaches or regional selectors compare performances in a fairer way of several skiers born in different months of the same year.

Several studies have investigated the relative age effect in other sports (Helsen et al., 2005; De la Rubia Rianza et al., 2020; Nolan & Howell, 2010; Rhys et al., 2018; Stephen Copley et al., 2019). This work is the first one to quantify RAE in French alpine

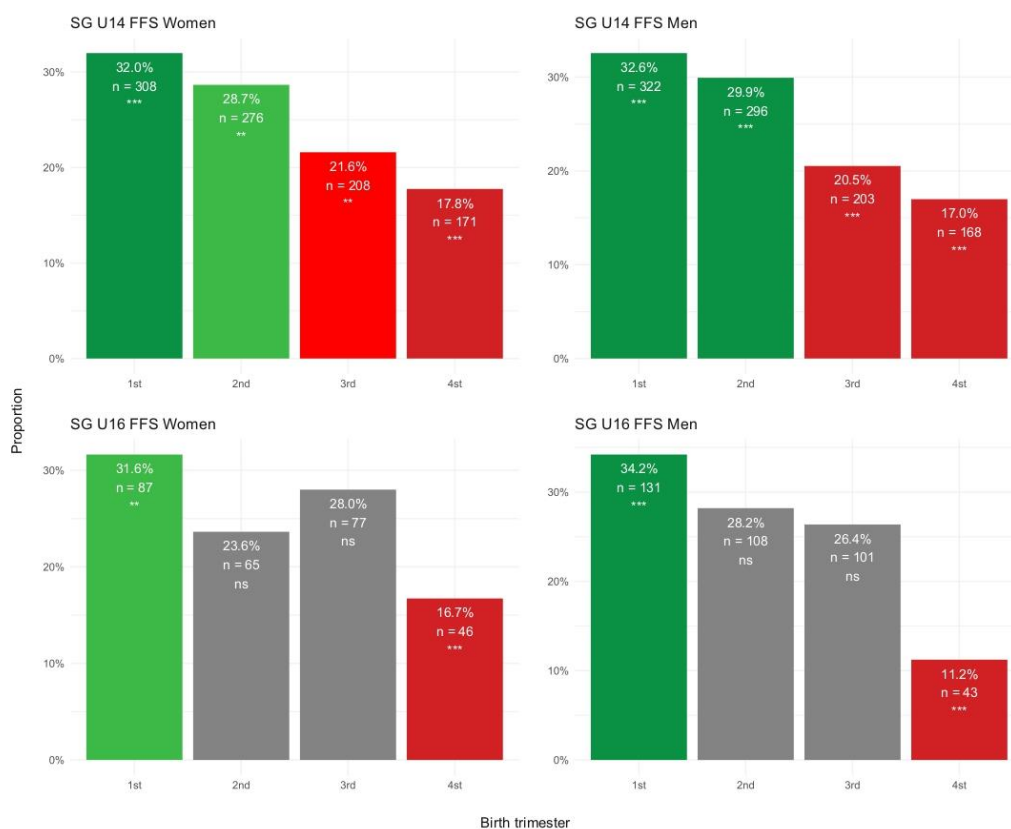


Figure 8. Distribution of terms of birth by category for elite youth competitions (FFS U14 above and FFS U16 below) and each gender (male on the right and female on the left) in SG.

skiing disciplines. Development between 13 and 18 years has already been studied in other studies (Bottollier et al., 2020). The strong physical component of alpine skiing, with important energy needs partly explains why relatively older individuals find themselves advantaged in performance. The link between physical and cognitive abilities and RAE exists (Huertas et al., 2019) but some studies do not observe it (Carling et al., 2009). It also depends on the selection criteria developed to reach the high level in the different sports.

The global relative age effect is probably due to the fact that selections at youngest ages are mostly made on the sole criterion of performance. Individuals in the same age category but months older have more time to further develop their physical, physiological and psychological characteristics (W. F. Helsen et al., 2000). Diry et al. (Diry et al., 2020) showed this dependence on maturity of physiological factors for rowing. Another study reinforced this hypothesis, showing that the relatively older male competitors were significantly taller and heavier than the younger competitors in youth winter Olympics (Raschner et al., 2012). Like in other studies, the RAE is

exacerbated in the youngest categories and wanes in the proximity of the senior categories (Johnson et al., 2017; Smith et al., 2018; Votteler & Höner, 2017), with a greater presence of RAE in adulthood in men than in women (Boccia et al., 2021). This persisting effect in senior categories can find explanations probably because the skiers selected in the young categories benefit earlier from more investment in trainings, more experienced trainers and training partners, and the knowledges about the elite circuits, which facilitates their access to the highest level in adulthood. We therefore do not find here the so-called "underdog effect", that is to say an inversion of the proportions of birth trimester in adulthood, yet present in different team sports such as rugby (McCarthy & Collins, 2014) or basketball (De la Rubia Riaza et al., 2020). If this is not due to a statistical hazard, maybe team sports have more performance factors than alpine skiing which may lead to more subjective judgements from coaches which allow access even in late ages. Conversely, as in our study, we find a RAE in various individual disciplines, notably throws in athletics (Boccia et al., 2021; Brustio et al., 2019). These individual sports have performance

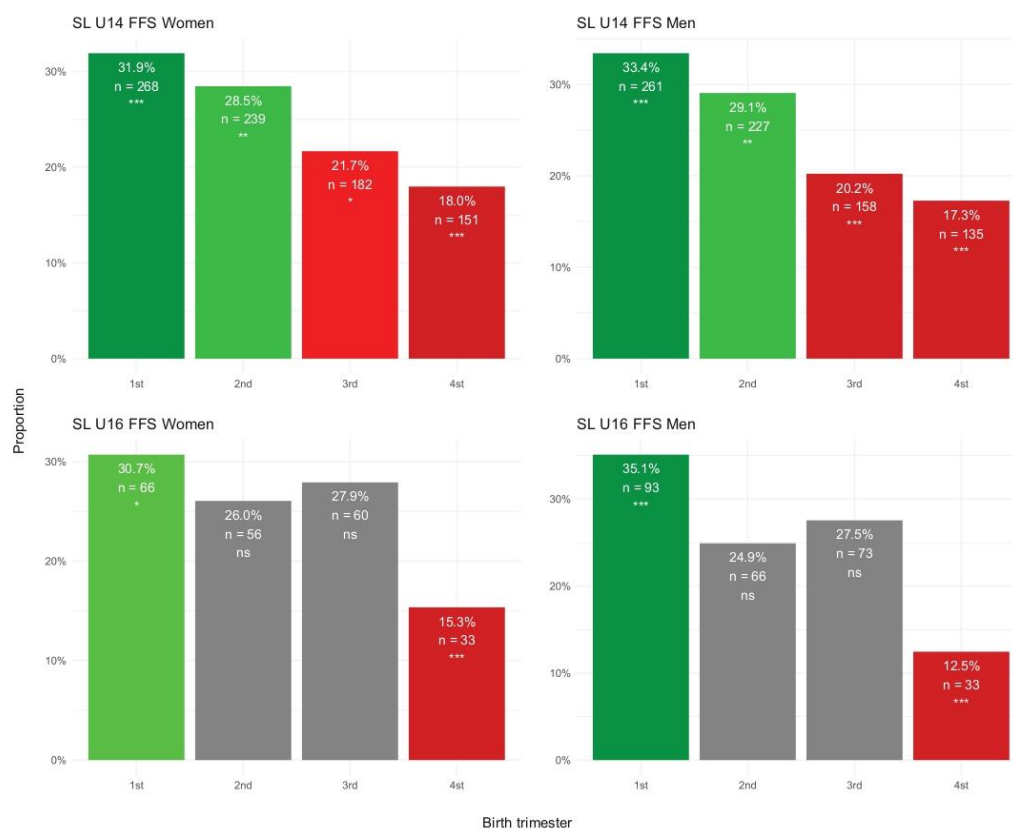


Figure 9. Distribution of terms of birth by category for elite youth competitions (FFS U14 above and FFS U16 below) and each gender (male on the right and female on the left) in SL.

determinants closer to alpine skiing. Selection methods, which offer future benefits, may be carried out early in an athlete's career, and leave little opportunity for new athletes.

The methods proposed so far (Barnsley & Thompson, 1985) have not made it possible to reduce the biases linked to the RAE (Nolan & Howell, 2010). These are indeed fair measures, but proposals such as reducing the ages for regrouping or setting up quota systems in elite selections are costly and difficult to implement from a logistical point of view on an entire population of young athletes. An interesting idea would be to carry out standardized and quantifiable physical, physiological, psychological and sociological tests at regular intervals to monitor, on multiple indicators, long-term performance (several years). However, unlike the method proposed in this study, this approach can be complex to set up and requires individual monitoring over the long term.

Our method is easy to set up and allows for a faster adaptation of institutional practice with regard to detection and selection of young people. This method is similar to what has been

previously suggested in swimming sprint disciplines (Abbott et al., 2020; Romann et al., 2015; Shaun et al., 2021; Stephen Copley et al., 2019). The authors have used a linear regression between performance and chronological age to determine the potential gain in terms of performance according to the swimmer's birth period. Their adjustment procedures, obviously, performances do not progress linearly; it follows a double intertwined exponential (Geoffroy Berthelot et al., 2019), but for the sake of implementation simplicity, compensation can be approximated through a linear relation over a 12 month period.

Both methods allow researchers and coaches to compare in an equivalent manner all the swimmers of the same category regardless of the month of birth. This has two main practical advantages: in the short term, individuals may have their performances rebalanced in a fairer way for their real age. In the long term, individuals who were previously unselected due to their period of birth may reintegrate into a long-term training programme for young skiers and the paths of high performance and thus be able to more easily exploit their potential

to reach the top level. The method is simple to apply and could be integrated directly into the coaches monitoring tools, providing a more accurate evaluation of the performance of young skiers.

Practical application

This study therefore makes it possible for the coaches and federal staff of young skiers to become aware of the presence of a relative age effect in French alpine ski. We show that it may be necessary to assess young athletes based on potential performance and not the current one only. Second, this study proposes a method to better compare skiers of different chronological ages, integrating the RAE in a given category. For example, if two skiers have similar performances but at different chronological ages, the calibration coefficient method will give the youngest one a fairer evaluation, suggesting a higher potential in the future. The proposed method does not recommend selecting athletes with a best potential estimated by our model, it aims to provide this additional information to make a decision. The person using the decision support tool, i.e. the coach or federal staff, for example, will then adjust these coefficients himself by his personal knowledge. It is therefore a first step towards correcting the bias of the RAE in French alpine skiing. Skiers may no longer miss certain selections unfairly, while the federation can acquire a more accurate assessment of its young categories, which will better support long-term potentials by rebalancing the chances from the beginning.

Limitations and perspectives

The present study has two main limitations. First, the calibration equations depend on a performance dataset with a 15-year follow-up only. The volume of data is more important for the young categories and decreases over time. Hence, there is a greater uncertainty regarding the calibration coefficient in the adult ages. However, the proposed method will get more precise as new data entries will increase the robustness of the model. In addition, the confidence interval of the coefficient makes it possible to add a nuance taking into account the sample size and the outliers. The second limitation of this study is that it only considers the age and performance variables to correct for the RAE. It would be interesting to take into account other factors allowing to calculate biological maturity (Mirwald et al., 2002) and its influence. It may therefore be worthwhile to include biological/biometrical variables of interest (height, seat height, leg length ...) or other parameters of the ski and compare the performances of skiers according to the progression of these variables also. The method is mainly based on easily retrievable performance and age data, it would be interesting to apply it to other sports whose performance is measured quantitatively.

Conclusion

A relative age effect is present in all youth age categories of the French alpine skiing. In the French national ski teams, skiers born at the beginning of the year are over-represented compared to those born at the end of the year. This effect is also present in adulthood on the International Elite Circuit (FIS). We

propose an easily implementable calibration method that corrects for such a bias. By adjusting the FIS points of each skier according to their month of birth, it allows for a fairer and more accurate performance evaluation. Ultimately, this tool could help rebalance the chances of reaching the highest levels, regardless of the month of birth.

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ORCID

Nicolas Coulmy  <http://orcid.org/0000-0003-3400-4619>

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EDITED BY
Tarak Driss,
Université Paris Nanterre, France

REVIEWED BY
Frédérique Hintzy,
Université Savoie Mont Blanc, France
Jeremy Coquart,
ULR 7369 - URePSSS - Unité de
Recherche Pluridisciplinaire Sport Santé
Société, France

*CORRESPONDENCE
Quentin De Laroche Lambert
✉ quentin.delaroche.lambert@insep.fr

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Potential estimation model in French alpine skiing - Individual evolution curve and progression typology

Quentin De Laroche Lambert^{1,2,3*}, Kilian Barlier², Imad Hamri²,
Audrey Difermand², Adrien Sedeaud²,
Jean François Toussaint^{2,4}, Juliana Antero², Pierre-Yves Louis^{1,5}
and Nicolas Coulmy³

¹Institut de Mathématiques de Bourgogne, UMR 5584 CNRS, Université Bourgogne Franche-Comté, Dijon, France, ²Institut de Recherche bioMédicale et d'Epidémiologie du Sport, EA7329, INSEP, Université de Paris, Paris, France, ³Scientific Department, French Ski Federation, Annecy, France, ⁴Centre d'Investigation en Médecine du Sport, Hôtel-Dieu, Assistance Publique, Hôpitaux de Paris, Paris, France, ⁵Institut Agro Dijon, PAM UMR 02.102, Université Bourgogne Franche-Comté, Dijon, France

Estimating the potential of alpine skiers is an unresolved question, especially because of the complexity of sports performance. We developed a potential estimation model based solely on the evolution of performance as a function of age. A Bayesian mixed model allowed to estimate the potential curve and the age at peak performance for the population (24.81 ± 0.2) and for each individual as the uncertainty around this curve. With Gaussian mixtures, we identified among all the estimates four types of curves, clustered according to the performance level and the progression per age. Relying on the uncertainty calculated on the progression curve the model created also allow to estimate a score and an uncertainty associated with each cluster for all individuals. The results allows to: i) describe and explain the relationship between age and performance in alpine skiing from a species point of view (at 0.87%) and ii) to provide to sport staffs the estimation of the potential of each individual and her/his typology of progression to better detect sports potential. The entire methodology is based on age and performance data, but the progression identified may depend on parameters specific to alpine skiing.

KEYWORDS

clustering, age, performance, mixed model analysis, bayesian

1 Introduction

Assessing the potential of young talents in top-level sport is still an unresolved question (Vaeyens et al., 2008; McCall et al., 2017). Success may depend on the athletes' fitness, characteristics, as on their environment and luck. Individual capacities can be grouped by intellectual, creative, socio-affective, sensorimotor and physical qualities (Vaeyens et al., 2008). The reason for this difficulty in estimating the future potential of an

athlete lies in the multi-factorial aspect of individual progression (Vaeyens et al., 2008; McCall et al., 2017). That performance and performance progression is linked to the development of aerobic power, muscular endurance, motor skills as well as overall intelligence. The development of all of one's abilities does not take place at the same time for all individuals (Katzmarzyk et al., 1997). As a result, selections made at an early age can generate many biases, starting with the relative age effect (DeCouto et al., 2021; De Laroche Lambert et al., 2022; Roaas et al., 2022). A retrospective study (Boccia et al., 2017) shows that only 10–25% of elite adult athletes were elite at age 16 in Italian high jump and long jump. Around 60% of top performers at age 16 did not maintain the same level of performance as adults revealing the interest of not focusing too early on the performance level. In practice, the systems for detecting young talents force us to reduce this complexity by "a) the performer; b) the environment; and c) practice and training" (Rees et al., 2016).

Recently, statistical methods have attempted to provide answers to the problem of estimating potential, closely linked to the relationship between age and performance. The relationship between age and performance has been theorized (Moore, 1975) in 1976 in different athletic disciplines as a sum of two exponential laws, one increasing characterizing the phase of performance progression and the other decreasing for the phase of decline. The intersection of these two exponential laws determines the performance peak. The author used this equation to model the relation between age and performance in different athletic running disciplines, from 100 m to marathon, but also throwing disciplines such as shot put and discus. This equation (Berthelot et al., 2012) allows to model the relation between age and performance in 25 Olympic sporting events and among chess grandmasters. The estimated age of peak performance is calculated at 26.1 years for the events studied (26.0 years for athletics, 21.0 years for swimming and 31.4 years for chess). Age explained 98.5% of performance variability at the species level. From an individual point of view, the authors modeled each of the individual trajectories with Moore's equation ($R^2 = 91.7$), but this raises some issues. Usually the number of performance available per individual is too low compared to the complexity of the described equation which has 4 parameters. Also, each individual model does not consider the relationship between age and the performance of the entire population. More recently, this relationship (Berthelot et al., 2019) has been modified by an equation with 1 parameter in addition to that of Moore taking into account the biological characteristics, especially at young ages. But these models are always carried out from a species point of view and do not take into account intra-individual variability. In addition this equation has never been used in alpine skiing to model the relation between age and performance.

Such relation between age and performance makes it possible to characterize the capacities many physical and physiological variables inherent in athletic performance as a function of time such as strength (Mitchell et al., 2012), maximal oxygen consumption and the respiratory volume (Stanojevic, 2008), the volume of the pulmonary capillaries (Aguilaniu et al.,

2008), or the cognitive performance (Preuter-Lorenz, 2009). Hollings et al., using quadratic mixed models taking into account the influence of different factors (e.g. wind, altitude) estimate the average age optimal performance and its standard deviation for the population thanks to fixed effects (Hollings et al., 2014). They thus define age interval to which it would be preferable to belong, at the dawn of a major event such as the Olympic Games, to maximize their chances of performing well. Some authors deepen these works (Allen and Hopkins, 2015) by performing a meta-analysis to determine the age at peak performance no longer by sport category but by type of effort (explosive, endurance, mixed) and by duration of effort. They thus demonstrated the logarithm relationship between the age at peak and the duration of the effort, in the case of explosive and endurance efforts. But again, these studies are retrospective and descriptive studies giving general information about the population, but the development of abilities depends on each individual (Lloyd et al., 2014), and therefore the relation between age and performance is unique to each individual. The importance of characteristics related to maturity (physical, technical and coordination) in young skiers (Gorski et al., 2014; Steidl-Müller et al., 2020) demonstrates the interest of studying the relationship between age and performance in this discipline. The peak of performance in alpine skiing has been shown to be 26 years old for women and 28 years old for men. (Müller et al., 2014). Yet, the methodology to estimate such age of peak performance relied on small samples on elite skiers. No study has been done on the completeness of a nation's data, despite the call for more longitudinal research in alpine ski (Steidl-Müller et al., 2019).

We therefore aim in this study to a) model the relationship between age and performance in French alpine skiing by taking into account individual variability b) identify typologies of performance progression c) estimate the cluster of an individual to help assess the potential and therefore improve the detection system.

2 Materials and methods

2.1 Description of the dataset

The methodology developed is presented for the male giant, but it is applicable to all disciplines (Slalom, Downhill, Giant and Super-G) and genders (female, male). The dataset includes all the performances achieved on the FFS (Fédération Française de Ski) and FIS (Fédération Internationale de Ski) circuit from the 2004/2005 season to the 2021/2022 season on male giant. 522,098 performances have been achieved by 25,083 skiers aged 10 to 25. Alpine skiing performance is quantified using FFS points. The number of points scored on D-day depends on the overall level of the race and the time achieved in relation to the winner of the race. The lower the number of points, the better the performance.

2.2 Estimation growth/decline model parameters

Moore (Moore, 1975) modeled the relationship between age and performance by a sum of two exponential laws intersected by the performance peak 1). More recently, a study (Berthelot et al., 2019) took over this model to create IMAP, an integrative model of age performance. To choose between these two functions, we used the methodology (Berthelot et al., 2019) by calculating the coefficient of determination R^2 and the adjusted R^2 on the age and performance data on best performance by age using the method of least squares. Moore's model was chosen because it had bigger R^2 (0.9267 versus 0.9198).

$$P(t) = a \cdot (1 - e^{-bt}) + c \cdot (1 - e^{dt}) \quad (1)$$

with $p(t)$ performance at age t and a, b, c, d the model parameters.

Contrary to the data in athletics which had been used by Moore, FFS points is to be minimized. We therefore adjust Moore's equation so that it is consistent with our context 2).

$$P(t) = a \cdot (e^{-bt}) + c \cdot (e^{dt}) \quad (2)$$

To take into account the intra-individual effect, we use Moore's equation to add around each fixed parameter, a random part for each individual i 3).

$$P_i(t) = (a + a_i)e^{-(b+b_i)t} + (c + c_i)e^{(d+d_i)t} \quad (3)$$

with a_i, b_i, c_i, d_i , the random parameters specific to each individual i .

2.2.1 Model features

To overcome counter-performances, the model is trained on the best performance by age per individual (14,838 performance achieved). The fixed and random parameters are estimated with a Bayesian model based on a Markov Chain Monte-Carlo Method (MCMC) with the No U-Turn Sampler algorithm (NUTS) (Hoffman and Gelman, 2011) proven on real simulated genetic data (Nishio and Arakawa, 2019). The *a priori* fixed parameters of the model are estimated using the ordinary least squares method on all performance. The model has four parallel chains of 200 iterations each. Such choice of the number of iterations was made to minimize both the complexity by reducing the number of iterations and to maximize the quality of the results by adding iterations. There will therefore be a total of 800 quadruplets of estimated parameters $\{a+a_i, b+b_i, c+c_i, d+d_i\}$ for each individual. Note that for a better convergence of the model, the performance data were centered and reduced then we added the minimum performance normalized so that all performance is strictly greater than 0. Age data was simply centered reduced.

2.2.2 Calculation of estimated progression potential

To calculate the progression potential curve and the intervals, we calculate for each individual the set (800) of potential Moore curves obtained with the different combinations of parameters $\{a+a_i, b+b_i, c+c_i, d+d_i\}$. Then, we calculate continuously (by age) the median of the estimates as well as the quantiles of the estimated trajectories according to the desired uncertainty.

2.3 Classification of estimated progression potential

2.3.1 Estimation of the different estimated progression potential

We carry out a classification based on Gaussian finite mixture modelling on the median of the parameters per individual. A model of Gaussian mixtures (Celeux and Govaert, 1992, 1995; Fraley and Raftery, 2002) estimates the distribution of random variables in modeling them as being the sum of several Gaussian components.

It is then necessary to determine the averages and covariance matrix of each of these Gaussian components. These parameters determine the geometric characteristics such as the volume, shape and orientation of the clusters (Scrucca et al., 2016). These settings being optimized according to the maximum likelihood criterion, using the procedure iterative expectation-maximization. We created 14 different models by varying the parameters of volume, shape and orientation.

There are several quality indicators of a clustering. However, we classify curves and no indicator is interested in their slope. We then defined an indicator of overlap of the distribution of derivatives between each pair of clusters.

Let $D_t = \{\{f'_i, f'_j\}, (i, j) \in \{1, \dots, K-1\}, \{2, \dots, K\}, i < j\}$ be the densities of the derivatives between each pair of clusters at the age t .

The Overlap score of model m is calculated as follows:

$$OS(m) = \frac{1}{K} \cdot \sum_{i=10}^{20} \sum_{k \in D_t} \int_{-\infty}^{\infty} \min(k(x)) dx \quad (4)$$

with K the number of clusters. The smaller the overlap score, the greater the densities of progression slopes over the ages between the clusters. The model with the lowest overlap score is selected.

A graphical example of the calculation of the overlap between two clusters is shown in the Supplementary Figure S1.

2.3.2 Individual progress cluster estimate

The medians of the parameters of each individual having been used to identify the different clusters, we calculate for each

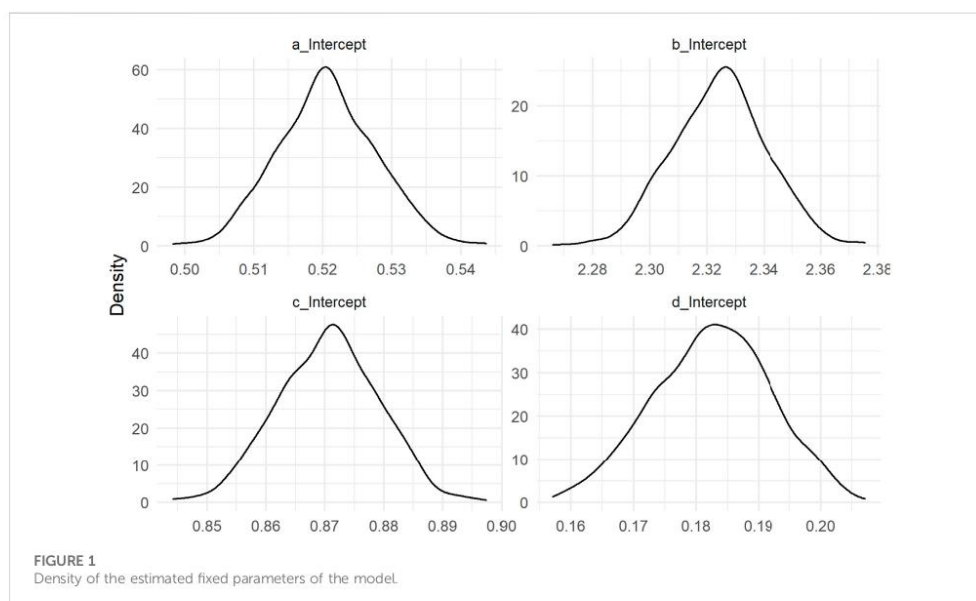


TABLE 1 Estimation of the median, standard deviation and quantile of order 0.025 and 0.975 of the parameters of the model.

	Estimate	Est.Error	Q2.5	Q97.5
a_Intercept	0.5206276	0.0071153	0.5075216	0.5345986
b_Intercept	2.3244675	0.0164799	2.2927248	2.3563620
c_Intercept	0.8705898	0.0086492	0.8539111	0.8865912
d_Intercept	0.1825503	0.0093500	0.1642391	0.1998790

individual the probability of belonging to each cluster for the 800 quadruplets of parameters. We then calculate the means and the confidence intervals of the probabilities of belonging to the clusters.

3 Results

3.1 Estimation growth/decline model parameters

3.1.1 Population

The distribution of fixed parameters a , b , c , d is shown in [Figure 1](#). The coefficient of determination R^2 is 0.87. In comparison, the R^2 obtained with only the least squares method without random effects is 0.3. The model parameters are presented in [Table 1](#).

The estimate of the relationship between age and performance (median \pm estimation interval) is presented in [Figure 2](#). We show that the age at peak performance in a French male Giant is estimated at 24.81 ± 0.2 for an average maximum performance estimated at 141.37 ± 1.05 ([Figure 2](#)).

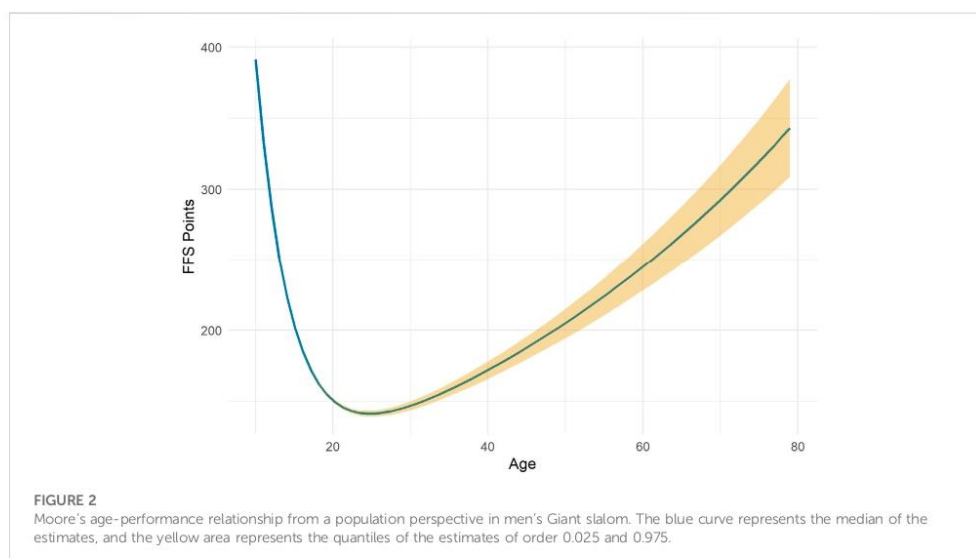
3.2 Individual

An example of estimating the individual potential curve and its interval is shown in [Figure 3](#). 800 estimation curves are estimated ([Figure 3A](#)) with the different quadruplets of parameters, then estimation intervals are calculated using quantiles of order 0.05 and 0.95 of the distribution of estimates ([Figure 3B](#)).

3.3 Classification of progression trajectories

3.3.1 Estimation of the different progression trajectories

The selected model with the best score in the metric proposed in 2.3.1 is a Gaussian mixture classification with equal volume, shape and orientation between clusters. The average performance trajectories of the clusters as well as the average derivatives are presented in [Figure 4](#).



The number of individuals for each cluster is respectively of 15,187, 243, 246, 354 for clusters 1, 2, 3, 4.

There are four distinct clusters:

- Cluster one represents the average cluster.
- Cluster two represents the cluster with the lowest progression slope.
- Cluster three represents the cluster with the strongest slope of progression.
- Cluster four represents cluster with lower performance.

3.3.2 Individual progress cluster estimate

Figure 3C shows the mean and the confidence interval of the individual probabilities in each cluster for the two individuals taken as examples. Individual 1 (right) is more likely to belong to cluster 1 (41%) while individual 2 (left) is more likely to belong to cluster 3 (35%).

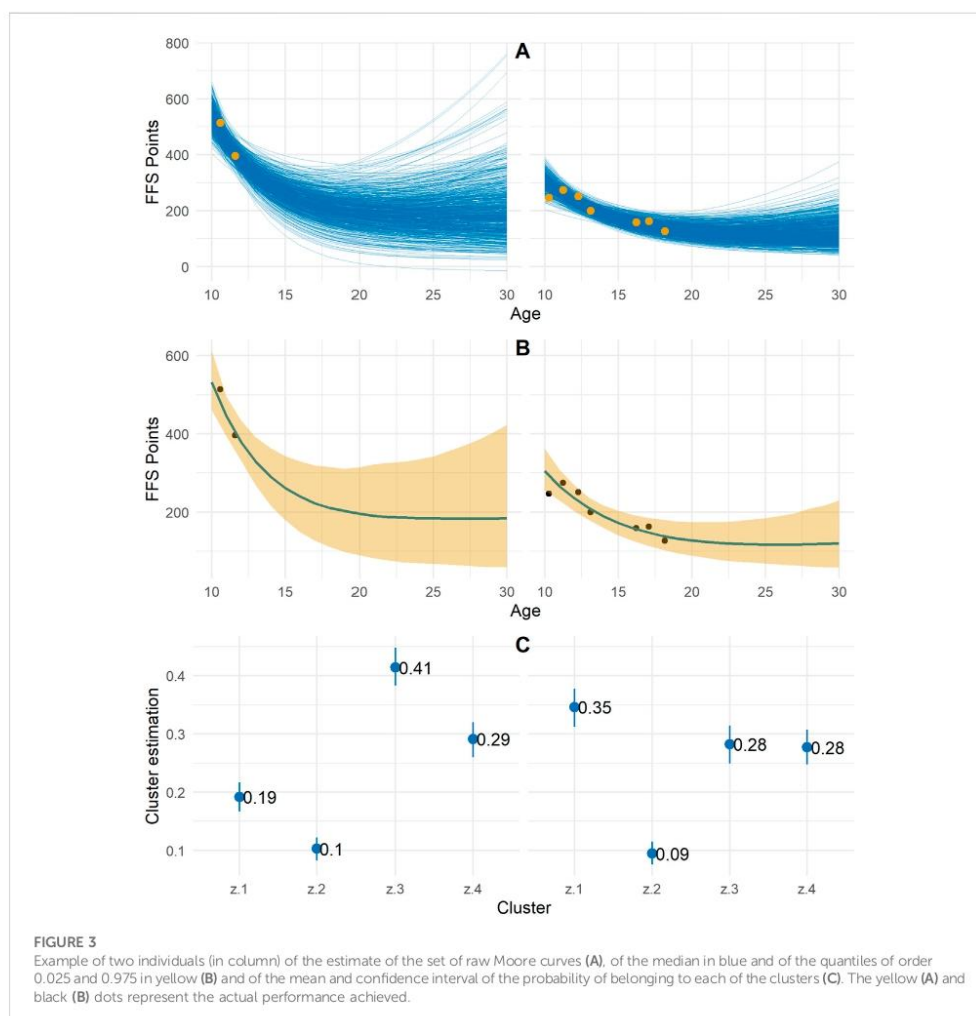
4 Discussion

We propose a method to individualize the relationship between age and performance in alpine skiing. We then identify four types of progression among all of these individual progressions. Finally, our method makes it possible to estimate with uncertainty the clusters most associated with each individual.

The relationship between age and performance has been studied only at the human scale (Moore, 1975; Berthelot et al.,

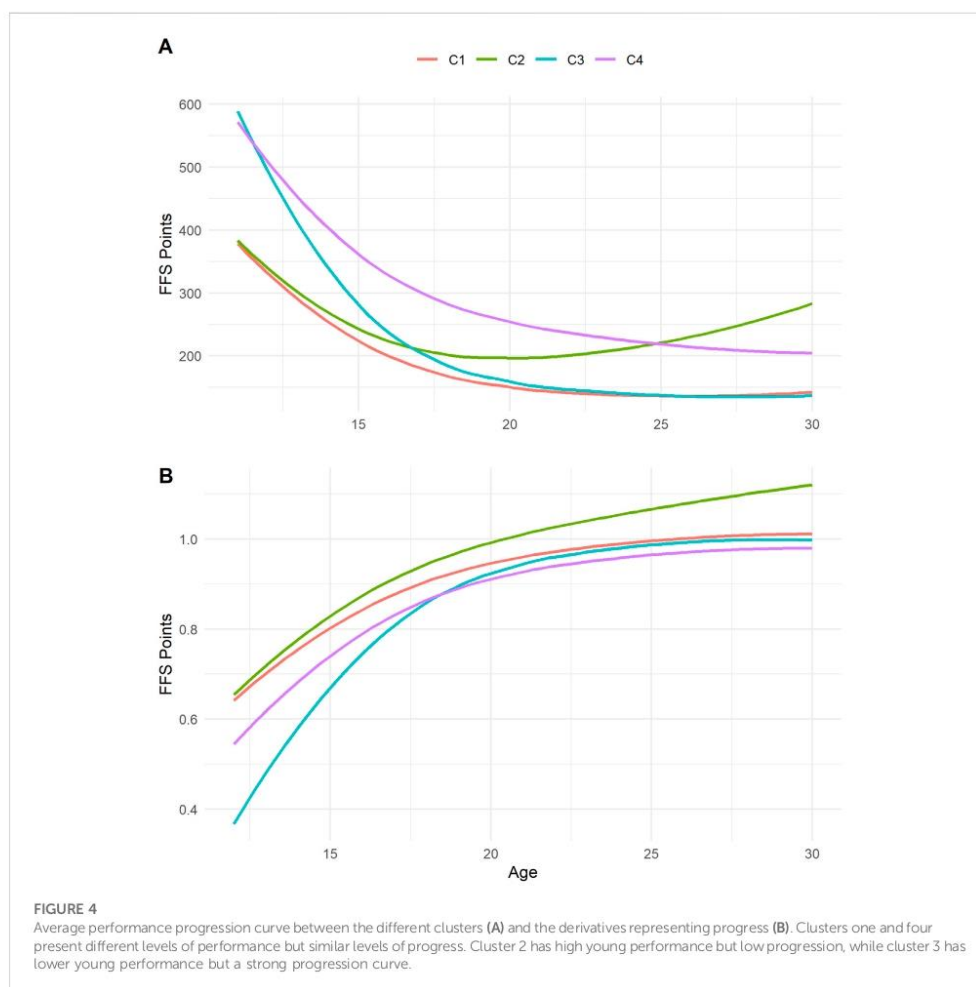
2012, 2019). This study is the first to model the age-performance relationship individually with random effects, taking into account the general law with fixed effects. Moreover, our model is the first to be able to estimate an uncertainty around the estimates. By principle of parsimony, in particular with the mixed model, we choose the model of Moore having a parameter of less. One of the limits of the study is to use the FFS points which is a relative performance compared to other skiers unlike a metric performance in swimming or athletics for example. However, the quality of the model (0.87) shows that the model adapts well to this measure.

Using another method, Hollings et al. estimated an optimal age for performance in different track and field disciplines between 25 and 27, which is close to the age at peak performance estimated by our male giant model. Muller et al. estimated, at the end of the 2012–2013 season for elite skiers, the peak age in men's alpine skiing was approximately 28 years. The almost 4 years of age-at-peak differences found here with previous studies can be explained by the different population and methodology used. Indeed, our study is based on the exhaustiveness of the performances achieved by French skiers since the 2004–2005 season, and is based on an functional age-performance statistical model used in other disciplines. Our model makes it possible to take into account the longitudinal aspect of performance, important when we know that it is difficult to precisely detect young talents before the age of 16 due to the rapid evolution before this age (Boccia et al., 2017; Kearney and Hayes, 2018). One of the strengths but also a



weakness of our model lies in the fact that only performance and age data are necessary to estimate an individual age-performance relationship. This means that all the components linked to performance are summarized in these two variables. Among these components, there is that of adaptation described by Pickering and Kiely (Pickering and Kiely, 2017). There are also of course all the physical components (Bottollier et al., 2020; Cross et al., 2021) or technical (Perić et al., 2019). To overcome the variability of performance due to all these variables, we take the record per year per individual. However, other

environmental variables can affect performance, such as injury or schooling. But it is also a strength because it requires very easily recoverable data. The method is therefore applicable to any discipline with quantifiable performance (such as swimming or athletics). One of the improvements of the model would therefore be to add other physical, psychological and environmental variables to the model, on which performance in alpine skiing depends (Bottollier et al., 2020; Cross et al., 2021), but it is more difficult to recover physical data at large scales than performance data.



Concerning the clustering, we first bring an interesting solution during a classification on longitudinal data when the individuals never have a complete trajectory, by carrying out the clustering on the more random fixed parameters of the mixed model (Figure 4). Clustering using finite Gaussian mixtures makes it possible, thanks to a parameter of the model (Fralely and Raftery, 1999), unlike the k-means method for example, to obtain clusters of unequal numbers. The algorithm determines the optimal number of individuals per cluster. The results show that the algorithm identifies an average cluster with the largest numbers, and clusters with particular trajectories, which would not have been identified with other clustering methods with

clusters of equal numbers. Then, we bring an interesting metric to differentiate the clustering of longitudinal data by their slopes outside the traditional Bayesian Information Criterion (Schwarz, 1978). In addition, our method makes it possible to individually obtain a score in each cluster for each individual with an uncertainty, which is not the case in other studies of clustering of progression trajectories which stop at the observation and the interpretation of the different clusters (Leroy et al., 2018). Given the importance of the physical, physiological and technical components in alpine skiing (Bacharach and Duvillard, 1995; Tumbull et al., 2009; Müller et al., 2017), the different clusters identified may correspond to

different physiological progression. Indeed, biological maturation does not take place at the same time for all individuals (Lloyd et al., 2014). This effect of maturity has shown its influence on the evolution of the performance of young athletes in different sports such as judo Giudicelli et al. (2021), football (Peña-González et al., 2022), rowing (Thiele et al., 2021) and basketball (Torres-Unda et al., 2016).

5 Practical application

Like other study before (De Laroche Lambert et al., 2022), this study aims to optimize the detection systems of French winter sports. We propose a methodology allowing to estimate the individual progress of the skiers, according to the relation between its performance and their age. Using this methodology, it is possible to implement, by extracting the random parameters of the model, a decision support tool for sports players (coaches, staff, skiers). The purpose of the study is to expose the whole of the methodology allowing to estimate the individual potential and shows the example for two distinct skiers, but does not show the results for all the individuals. The method developed estimates a large number of relationships between age and performance for each individual. As a result, the uncertainty around the estimated relationship is not to be interpreted as a confidence interval of the possible performances performed, but rather as a confidence interval of the potential of this individual, which can be called "Estimate Interval".

6 Conclusion

We propose a potential estimation method based on the relationship between age and performance to obtain the potential performance curve and the type of progression of each individual. We then estimate four progression typologies, and the probabilities associated with each of them for all individuals. The purpose of the method is to help those involved in French winter sports to better detect young talents, but also to show the relationship between age and performance in alpine skiing with regard to the physical specificities of the skiers, relying (Bacharach and Duvillard,

1995) on the analysis of large-scale longitudinal data (Müller et al., 2015). The method developed here can be extended to all sports with quantifiable performance.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: <https://ffs.fr/resultats/>.

Author contributions

QD and KB. conceived of the presented idea, developed the theory and performed the computations. QD, KB, IH, and AD verified the analytical methods. JT, JA, PYL, and NC supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer FH declared a past co-authorship with the author NC to the handling editor.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fphys.2022.1082072/full#supplementary-material>

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