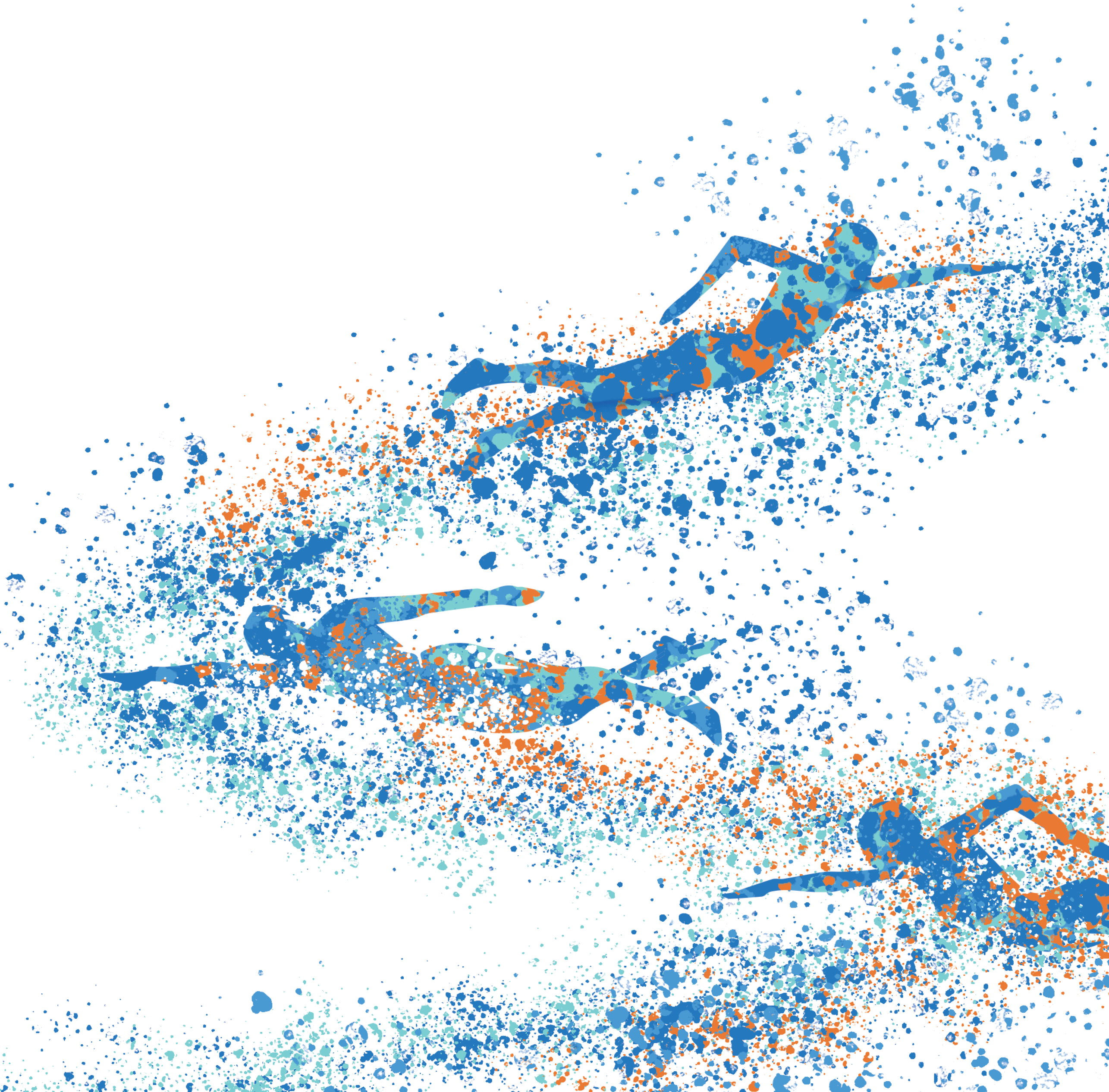
DEMYSTIFYING SWIMMING TALENT

Aylin Post



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The studies in this thesis were conducted within the Health in Context Research Institute of the University Medical Center Groningen (UMCG) and under auspices of the research program Smart Movements (SMART) at the Center of Human Movement Sciences, part of the University Medical Center Groningen, University of Groningen, the Netherlands. The printing of this thesis was financially supported by the Graduate School of Medical Sciences (GSMS) of the UMCG and the University of Groningen, InnoSportLab de Tongelreep and the Dutch Swimming Federation (KNZB).

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Dr. M.T. Elferink-Gemser
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Prof. dr. R.H. Koning

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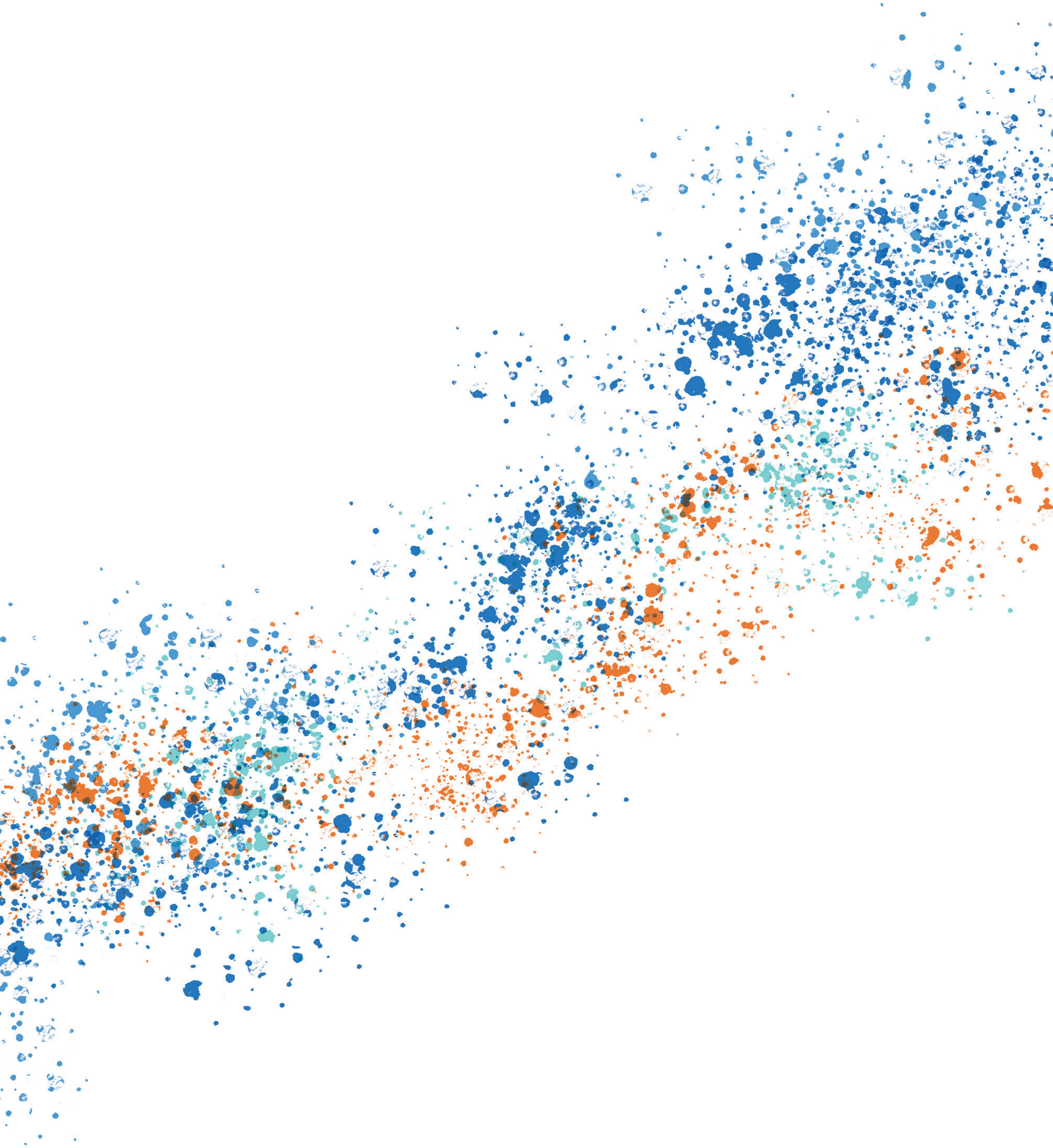

Chapter 1

General introduction

While champions thrive, a new wave of future stars quietly rises

As a sport known for its close margins where differences of just 0.03 seconds can determine victory or defeat, competitive swimming has a long history of success in The Netherlands. With an impressive tally of 62 Olympic medals up to 2024 (Olympian Database, 2024), Dutch swimmers have firmly established themselves as a force to be reckoned with, even when competing against swimming giants like the USA and Australia. Yet, we should not take this rich tradition of achievement for granted.

In a relatively small country like the Netherlands, the pool of potential world-leading swimmers is limited. Typically, there are only about 16 swimmers every four years who successfully navigate the long and challenging path that leads to participation in the Olympic Games (Olympian Database, 2024). Among them, a few get the opportunity to compete for top positions on the podium, following the footsteps of icons like Pieter van den Hoogenband, Inge de Bruijn and Ranomi Kromowidjojo.

Given this context, and even in the midst of remarkable achievements in the past and present, it is important to direct our attention towards the future. Who will be the next generation to rise and uphold the nation’s high standard of performance, and how can we best guide them on the journey towards the elite level? In other words: if we aspire to maintain our strong standing on the global swimming stage, we must truly excel in our efforts of finding and nurturing the upcoming wave of swimming talent.

Talent identification and development in Dutch swimming

Starting at the age of twelve, the Royal Dutch Swimming Federation (KNZB) initiates its endeavor to identify talented swimmers, aiming to provide them with optimal learning environments to accelerate or realize their potential towards swimming expertise (KNZB, 2024; Williams & Reilly, 2000). These talent development programs are designed to support promising swimmers with various benefits, including expert coaching, improved facilities, and the chance to train alongside other talented peers (KNZB, 2024). Unfortunately, due to capacity limitations in the talent identification and development (TID) system, coaches must decide who receives additional developmental opportunities, a privilege limited to a small group of selected swimmers only (Till et al., 2020).

The main source of information to make these selections are the swimmers’ season best times and how they rank nationally. This approach appears reasonable given that swimming is fundamentally about travelling a certain distance in the water as fast as possible (Barbosa et al., 2010a). Moreover, thanks to advancements in technology like electronic timekeeping and the availability of competition data online (Swimrankings, 2024; World Aquatics, 2024), collecting this information is both reliable and straightforward. However, while measuring swim performance in terms of fastest time is quite simple, figuring out which youth swimmers are most likely to succeed as adults is anything but that (Koz et al., 2012; Till et al., 2020; Güllich et al., 2014; Güllich et al., 2023; Schorer et al., 2017).

The complexity of athlete development

A major challenge in talent identification processes for coaches lies in the dynamic nature of athletes' capabilities, which are not fixed (Baker et al., 2019; Simonton, 2001). Rather than following a consistent upward trajectory, athletes develop along an unpredictable pathway marked by rapid progressions, plateaus, and setbacks (Abbott et al., 2005; Baker et al., 2018). This has been exemplified by studies showing that swimmers who were leading in their age category shifted to lower positions later on and vice versa over time (Barreiros et al., 2014; Brustio et al., 2021). According to the Groningen Sport and Talent Model, the changes in swim performance are driven by changes in underlying performance characteristics linked to the athlete (Elferink-Gemser & Visscher, 2012). These include the rate of learning, training and maturation of anthropometric, physiological, technical, tactical and psychological characteristics. At the same time, the environment plays a crucial role too with parents, coaches and talent development programs creating opportunities to support athlete development, for example by providing resources that facilitate high-quality training (De Bosscher & De Rycke, 2017; Henriksen et al., 2010; Henriksen & Stambulova, 2023; Marinho et al. 2020). All these factors have the potential to interact uniquely for each individual and, moreover, they can also change as someone's career progresses (Abbott et al., 2005; Simonton, 1999).

Therefore, in our efforts to identify and nurture promising swimmers, it is critical to acknowledge and act upon the complex nature of athlete development (Phillips et al., 2010; Ribeiro et al. 2021). Rather than solely focusing on swim performance as a stand-alone measure, which is often the case, we should also uncover the underlying performance characteristics that have contributed to what we see today. These factors may include swimmers' height, maximal swimming velocity, stroke index, proficiency in starts and turns, lower body power and the ability to train effectively and efficiently (Barbosa et al., 2010b; Jürimäe et al., 2007; Morais et al., 2017; Morais et al., 2019; Morais et al., 2021; Morais et al., 2022; Seffrin et al., 2022). Furthermore, it is important to get an understanding about a swimmer's developmental process over time. Failing to include this more sophisticated approach could result in missing out on future swimming stars, misallocating limited resources away from the most promising swimmers or falling short of unlocking swimmers' true potential. Such inefficiency and ineffectiveness is problematic at every level of the system - for The Netherlands as acknowledged swimming nation, but most of all, for those aspiring swimmers who count on us to help them in pursuing their dreams.

Towards a more refined understanding

The foundation of a more refined approach in TID rests upon a profound understanding of the pathway to swimming expertise, yet scientific knowledge in this matter is lacking. Many studies within competitive swimming have focused on isolated performance domains (such as biomechanics) and have been conducted cross-sectionally (capturing a singular moment in time), typically involving recreational or elite adults rather than talented youth swimmers (Costa et al., 2012; Morais et al., 2021). While such studies offer value for specific research inquiries, they fall short of providing insights into developmental trajectories linked to the elite level (Glazier, 2017). Longitudinal, multi-dimensional studies, on the other hand, are well-suited to detect developmental changes (Cobley & Till, 2017; Elferink-Gemser et al., 2018). Rather than relying on a single snapshot of performance, these studies track individuals over an extended period, evaluating multiple underlying performance characteristics in relation to their age and performance level. This approach empowers researchers to retrospectively analyze how swimmers who eventually reached the elite level progressed over time, as opposed to those who did not make it. Such examinations may uncover the defining factors and developmental patterns linked to senior success. These insights may provide science-based guidance to coaches and swimmers, and support informed decision-making processes in practice. Altogether, this may enhance the efficacy and efficiency of the TID system.

Thesis objective and outline

With the ambition to improve TID processes in swimming practice, this thesis aims to gain a deeper understanding of the pathway to swimming expertise. We specifically seek to make a meaningful contribution towards addressing the key characteristics and corresponding developmental patterns that set apart swimmers who succeed in their career from those who don't, spanning various developmental stages. In this pursuit, our focus rests on studying swim performance (in terms of swim times) and underlying performance characteristics linked to the swimmer by using a longitudinal and multidimensional approach..

Within this exploration, swimming expertise will be defined in relation to the elite level, signifying a performance level that aligns with the fastest 50 swimmers worldwide. However, while this standard is suitable for identifying senior elite swimmers, it lacks effectiveness for junior swimmers as it overlooks the significant developmental differences between age groups. Yet, the ability to differentiate which juniors are on track to reach the elite level is essential in our endeavor to uncover the pathway to swimming expertise, a challenge intensified by the absence of general developmental patterns of elite swimmers throughout their careers.

Therefore, the primary focus of the first part of this thesis is to gain a deeper understanding of the performance progression of elite swimmers. **Chapter 2** specifically explores the development of season best times for swimmers who achieved 1) top elite, 2) elite, 3) sub-elite and 4) high-competitive status in adulthood. By retrospectively analyzing the developmental patterns dating back to the age of twelve, this study aims to offer insights into when these four performance groups begin to differentiate. Additionally, age-related benchmarks to identify junior swimmers progressing towards the elite level in subsequent studies will be provided.

Building upon the results from Chapter 2, **Chapter 3** delves into a more detailed examination of performance progression within a single season. This study investigates whether talented swimmers who ultimately made it to the elite level are characterized with different patterns of interim performance progression (IPP) during two consecutive season best performances compared those who did not. The results of this chapter shed light on both the rates and timing of progression within a season.

The second part of this thesis centers on the contributing factors underlying swim performance, essentially examining the process leading up to the result. Within this context, **Chapter 4** investigates the development of pacing behavior in talented swimmers, specifically disentangling the effects of age and experience and differentiating between those who reached the elite level and those who did not. Whether swimmers who are on track to reach the elite level apply self-regulation of learning (SRL) subprocesses more frequently in their daily training sessions compared with swimmers who are not on this track will be explored in **Chapter 5**. In **Chapter 6**, talented swimmers in the late-junior-to-early-senior transition (males aged 16-19; females aged 15-18) will be analyzed. This chapter explores whether swimmers who are on track to the elite level at early senior age (males aged 19; females aged 18) show higher levels and progression of swim performance and underlying performance characteristics including, anthropometrics, starts, turns, maximal swimming velocity, stroke index and lower body power, compared to lower-performing peers during this transition. **Chapter 7** delves further back in time, investigating swimmers during their pubertal years (males aged 13-15; females aged 12-14). This study examines whether swimmers on track to the elite level at late junior age (males aged 16; females aged 15) demonstrate higher levels and progression on swim performance and underlying characteristics including, anthropometrics, maximal swimming velocity, stroke index and lower body power. In **Chapter 8**, the overall findings of this thesis are discussed, providing future directions and recommendations for swimming practice.

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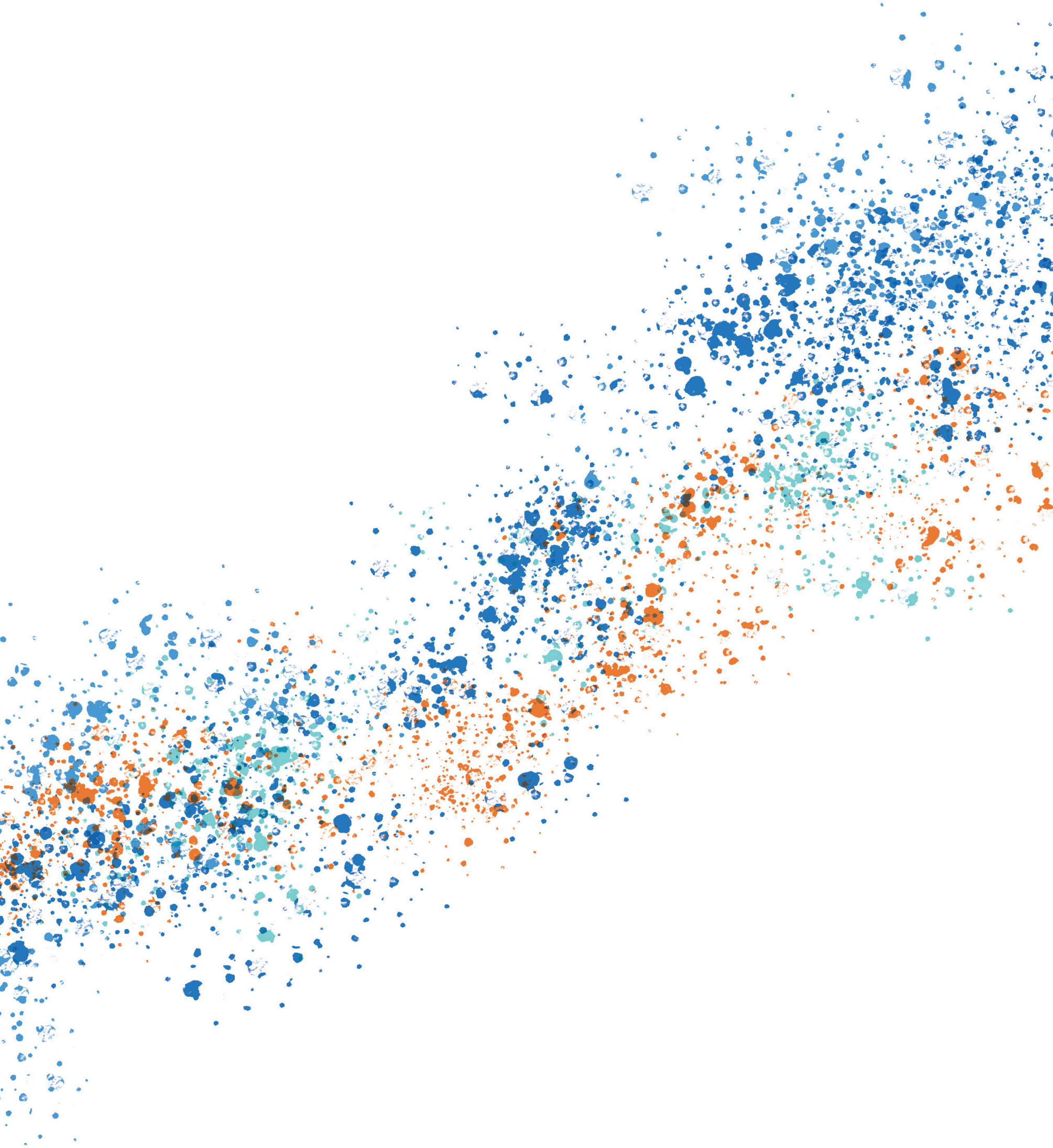

Chapter 2

Multigenerational performance development of male and female top-elite swimmers: A global study of the 100 m freestyle event

Post, A. K., Koning, R. H., Visscher, C., & Elferink-Gemser, M. T. (2020). Multigenerational performance development of male and female top-elite swimmers: A global study of the 100 m freestyle event. *Scandinavian Journal of Medicine & Science in Sports, 30*(3), 564-571. https://doi.org/10.1111/sms.13599

Abstract

Background

The present study investigated longitudinally the performance development of a multigenerational sample of competitive swimmers. The aim of the study was to provide unique insight into the junior towards senior performance development of those few who reached top-elite level. Season Best Times (SBT) of 100m freestyle performance of international swimmers, (1,305 males, aged 12-26 and 1.841 females, aged 12-24) competing in at least five seasons between 1993 and 2018, were corrected for the prevailing world record (WR). Swim performance was defined as a relative measure: relative Season Best Time=(SBT/WR)*100. Based on rSBT, four performance groups were defined: top-elite, elite, sub-elite and high-competitive.

Results

Univariate analyses of variance showed that male top-elite swimmers outperformed high-competitive swimmers from the age of 12, sub-elite swimmers from the age of 14 and elite swimmers from the age of 18 while female top-elite swimmers outperformed high-competitive and sub-elite swimmers from the age of 12 and elite swimmers from the age of 14 (p <0.05). Frequency analysis showed that male top-elite swimmers for the first time achieved top-elite level between the 17 and 24 years old (mean age of 21) while female top-elite swimmers started to perform at top-elite level between the 14 and 24 years old (mean age of 18).

Conclusion

Male and female top-elite swimmers are characterized by a high performance level from 12 years on and progressively outperform swimmers from similar age. However, this goes together with a large variety in the individual pathways towards top-elite level within and between sexes.

Keywords

Competitive swimming, sport performance, world record, talent, acquisition of expertise.

Introduction

In the context of athlete development, the increase of sport performance of a youth athlete aiming to make it to the top is key (Ericsson et al., 1993). In a relatively short time, young athletes will have to continue improving their sport performance to reach excellence (Ericsson et al., 1993; Wiersma, 2000; Elferink-Gemser et al., 2011). Knowledge about general performance development of those who have made it to the top could provide important information for athletes, coaches and federations (Allen et al., 2014). A thorough understanding of performance development during an athlete's career could facilitate the identification and development of talented athletes and could enable sport federations to target their support towards those athletes who have the greatest potential to make it to the top (Durand-Bush & Salmela, 2002).

A fitting sport to investigate the performance development of youth athletes on their way to the top is competitive swimming. Competitive swimming is a time trial sport in which a swimmer tries to travel a certain distance in the water as fast as possible. It is a popular global sport with a high level of competition in which the gap between the gold medalist and the last finisher in international competition is constantly decreasing (Stanula et al.,2012).

The key distance in competitive swimming is the 100m freestyle long course event, which has been on every Olympic program since 1904 (men) and 1912 (women). In this event, competition starts from an early age on and the competition level is high for both male and female swimmers (Swimrankings, 2018; FINA, 2018). Due to technological progressions like electronic timekeeping and online accessible repeated-measures competition data, retrospective studies on performance data of swimmers in the 100m freestyle event offer great opportunities to provide new insights for performance development in competitive swimming.

The time-captured nature of competitive swimming comes with a strong emphasis on swim performance from a young age on. In practice, this is marked by the early selection of the fastest youth swimmers into athlete development programs based on their competitive performance times (KNZB, 2018). The underlying assumption behind this approach is that future winners can be identified on the basis of their junior swim performance (Baker et al., 2018). In this way, swim performance from a young age on is highly valued and considered as a serious predictor of success (KNZB, 2018).

Nevertheless, the utility of talent identification on the basis of performance at early ages has been questioned by several researchers (Elferink-Gemser et al., 2011; Gulbin et al., 2013; Vaeyens et al., 2008; Règnier & Salmela, 1993). Specific for competitive swimming, research from Barreiros et al. (2014) has shown that the conversion rates of junior elite swimmers into senior elite swimmers are generally low. Moreover, one of the concerns of using this approach is the fixed focus on the swimmer's current performance level rather than the swimmer's potential performance level. This risks the exclusion of talented swimmers who may not be the fastest yet, but who may be so in the future (Elferink-Gemser et al., 2011; Elferink-Gemser et al., 2018). Scientific-based knowledge about the general performance development of top-elite swimmers throughout their entire career may enlighten the value of this approach.

Research on adult elite swimmers has given valuable insight into performance progression and the age of peak performance. The study of Pyne et al. (2004) showed that performance progression by ~1.0% within a competition and ~1.0% within the year leading up to the Olympics is necessary to stay in contention for a medal at the Olympic Games. Allen et al. (2014; 2015) modelled the career performances of Olympic top-16 swimmers and concluded that elite male swimmers achieve their peak performance at ~24 (± 2) years while elite female swimmers achieve peak performance at ~22 (± 2) years. The difference in age of peak performance between sexes can presumably be explained by the in general ~2-year earlier onset of puberty in females compared with males (Baxter-Jones & Sherar, 2006). Given this information, a comparison of the performance development between young male and female swimmers is of considerable interest as differences in performance development between sexes may hold important implications for training and athlete development programs. Both aforementioned studies provide valuable information about performance development of senior elite swimmers during adulthood, however, insight regarding the performance development during their younger years relative to swimmers who did not reach elite level is lacking. Big data analyses over multiple generations could provide relevant information about how elite swimmers got to their high level of expertise. What characterizes their successful performance development over the years compared to those who did not make it to the top?

The present study investigates the 100m freestyle performance development of a multigenerational sample of swimmers in order to provide more insight into the junior towards senior performance development of those few who reached top-elite level. Each research question is answered separately for male and female swimmers. The research questions we aim to answer are (1) From which age on do top-elite swimmers outperform swimmers from other performance groups (e.g. high-competitive, sub-elite and elite)? (2) From which age on do top-elite swimmers start to perform at high-competitive level, sub-elite level, elite level and top-elite level? The results of this study add value to both science and sport practice as it broadens the knowledge about general performance development of top-elite swimmers. It may function as a guideline for athlete development programs by providing scientific-based knowledge about the performance development of top-elite swimmers.

Methods

Ethical approval

All procedures used in the study were approved by the Local Ethical Committee of the University Medical Center Groningen, University of Groningen, The Netherlands (201900334) in the spirit of the Helsinki Declaration with a waiver of the requirement for informed consent of the participants given the fact that the study involved the analysis of publicly available data.

Data collection

The swimmers we selected for this study were international male and female swimmers with performance data on the 100m freestyle long course event. Performance data was obtained from Swimrankings (Swimrankings, 2018), a recognized public data source which records swimming race results. Performance data was collected from 113 countries across different parts of the world including Africa, America, Asia, Australia and Europe. We collected all available 100m freestyle long course results from Swimrankings' database, which initially resulted in 2,683,412 observations between 1993 and 2018.

Data processing

Performance data from the 1st of January 2008 till the 1st of January 2010 were excluded from analysis. During that time, swimmers were allowed to wear newly introduced full-body polyurethane swimsuits which led to a major benefit of the swimmers' drag force reduction (Tiozzo et al., 2009; Toussaint et al., 2002; Tomikawa & Nomura, 2009). From the 1st of January 2010 onwards, FINA banned these suits. Swim performances over 180seconds were excluded from analysis to ensure a representative dataset. A total of 2,383,616 observations was remained.

Based on swim dates, performance data were classified in swimming seasons. Each swimming season officially starts on the first of September of a calendar year and ends on the 31st of August of the next calendar year (1st of September 2018 till 31st of August 2019 corresponds to swimming season 2018/2019). Swimmers were classified in age categories based on their age on the 31st of December of the swimming season (a girl who is 14 years old on the 31st of December 2018 would be classified in age category 14 year for swimming season 2018/2019). Therefore, all ages mentioned in the present study refer to the age category in which a swimmer participated during the swimming season and not the calendar age of the swimmer. For each swimmer, we selected one Season Best Time (SBT) per swimming season which we used for further analysis. A total of 1,131,963 observations was remained.

Inclusion criteria

For the purpose of this study, it is important to outline the individual performance development from a young age on towards the adult age of peak performance (or beyond). Therefore only those swimmers who; 1) were between 12 and 24 years old (female) or between 12 and 26 years (male) old; 2) were in competition for at least 5 seasons; 3) had at least one SBT within the age category of 16 years or younger; and 4) had at least one SBT within the age category of 20 years (female) or 22 years (male) or older were included (Allen et al., 2014; 2015). This resulted in 5,636 individual swimmers (3,259 female, 2,377 male) with 40,063 SBT's (22,239 female, 17,824 male) with an average of 7.6 ± 2.1 observations per swimmer.

Defining swim performance and performance development

The present study includes swim performances of multiple generations, necessitating the correction of evolution in a given sport (Stoter et al., 2019). The continuous increase in world-class performances at Olympic Games and World Championships clearly reflects the evolution in a sport, as well as the improvement of world records (Stanula et al., 2012; König et al., 2014). For example, at the 100m freestyle event, the world record for females has been improved from 54.48 seconds to 51.71 seconds with 2.9 seconds (~5.3%) from 1994 to 2017 (FINA) and for males from 48.42 seconds to 47.04 seconds (fastest time in textile) with 1.38 seconds (~2.9%).

To correct for evolution in competitive swimming, we use a method to compare performance over multiple generations, introduced and validated by Stoter et al. (2019). First, each swimmer's SBT per swimming season between 2018 and their earliest available competitive performance was determined. Second, SBT's were related to the prevailing world record (WR) or the fastest time in textile of the corresponding sex. The prevailing WR is the official WR at the date the athlete swam the SBT. WRs from 2008 or 2009 were replaced by the prevailing fastest time in textile. The corrected SBT will be referred to as relative Season Best Time (rSBT) and is presented as a percentage of the world record or fastest time in textile. In this study, rSBT defines swim performance (see equation 1).

$$\text{rSBT} = \left(\frac{\text{SBT}}{\text{WR}}\right) * 100\% \qquad \text{(eq. 1)}$$

Defining performance levels and groups

Four performance levels were defined; top-elite, elite, sub-elite and high-competitive. Each performance level was characterized by sex-specific limits to account for differences in competition level between males and females (Table 1). The limits were calculated as the mean of 5 rSBTs for the xth swimmer from either the 100m freestyle performance FINA World Ranking Lists of 2014-2018 (FINA, 2018) or the 100m freestyle performance National Ranking Lists of the Netherlands 2014-2018 (Swimrankings, 2018). The limits of the top-elite performance level were based on rSBTs of the 8th male and female swimmer of the FINA World Ranking List 2014-2018 (e.g. rSBT 8th male swimmer 2014 + rSBT 8th male swimmer 2015 + rSBT 8th male swimmer 2016 + rSBT 8th male swimmer 2017 + rSBT 8th male swimmer 2018 / 5) . The other limits were defined so that they represented the 50th male and female swimmer of the FINA World Ranking List 2018 (elite performance level) and the 8th and 50th male and female swimmer of the National Ranking List of the Netherlands of 2018 (sub-elite and high-competitive performance levels respectively).

We determined each swimmer’s current performance group by allocating the rSBT of a given season to one of the four performance levels. For example, if a 16 year old boy has a rSBT of 108%, his current performance level corresponds with the limits of the high competitive performance group. Next, we determined each swimmer’s best performance group by allocating the best rSBT ever to one of the four performance levels, meaning that a swimmer either once or multiple times has reached this performance level at any age. For example, if a boy has a best rSBT ever of 105%, his best performance level corresponds with the limits of the sub-elite performance group. A swimmer’s current performance group is a dynamic variable and may change over time, whereas a swimmer’s best performance group remains static. Swimmers with a best rSBT ever outside the limits of the high competitive level (best rSBT>114.1% for males and best rSBT >114.6% for females) were excluded from further analysis (a total of 16,406 observations). Moreover, outliers were excluded (a total of 647 observations) using stem-and-leaf plot, as swimmers might have a poor season due to injury, illness or other reasons, which are not representative for the swim performance of swimmers in the corresponding performance group. Table 2 presents the male/female distribution and the number of observations (i.e., rSBTs per swimming season) for each performance group included for the analysis on swim performance.

Table 1. Limits of performance levels for males and females separately.

	Males	Females
Top-elite	rSBT <102.2%	rSBT <102.8%
Elite	102.2% <> rSBT < 104.0%	102.8% <> rSBT < 105.5%
Sub-elite	104.0% <> rSBT < 107.9%	105.5% <> rSBT < 108.0%
High-competitive	107.9% <> rSBT < 114.1%	108.0% <> rSBT < 114.6%

Table 2. Total number of swimmers (N = 3,146) and observations (N = 23,010) for each performance group for the analysis on swim performance (rSBT).

	Males		**Females**	
	Individuals	*Observations*	*Individuals*	*Observations*
Top-elite	29	274	57	504
Elite	62	582	218	1,734
Sub-elite	394	3,265	378	2,786
High-competitive	820	6,059	1,188	7,806
Total	1,305	10,180	1,841	12,830

Defining first entry ages

For top-elite swimmers only, we determined the first entry age of each performance level. The first entry age is the minimum age at which a swimmer for the first time achieved a higher performance level (e.g. performance level transition from sub-elite level to elite level). First entry ages for skipped performance levels (e.g. a performance level transition from sub-elite level to top-elite level) were not reported.

Statistical analysis

All data were analyzed for male and female swimmers separately using IBM SPSS Statistics 24 and R. Mean scores and standard deviations were calculated for swim performance (rSBT) for the four performance groups per age category. Per age category, a one-way independent analysis of variance (ANOVA) was used to examine group differences based on rSBT with performance group as independent variable. Planned contrasts were performed to determine differences between top-elite swimmers and swimmers of other performance groups per age category. A frequency analysis with first entry age as variable was executed for top-elite swimmers only. Mean scores and frequency distribution tables of first entry age were produced for the four performance levels (high-competitive level, sub-elite level, elite level and top-elite level). Statistical tests were executed for the age categories in which there were more than two observations in the top-elite performance group. For all tests, $p < 0.05$ was set as significance.

Results

Differences in swim performance between top-elite swimmers and other performance groups

Figure 1 illustrates the performance development of male and female swimmers on the 100m freestyle from age 12 to 26 (males) and 12 to 24 (females) specified for each of the four performance groups.

For males, there was a significant effect of best performance group on rSBT from age 12 till 26 (p <0.05). Planned comparisons between the top-elite performance group and other performance groups revealed that from the age of 12, top-elite swimmers performed better than high-competitive swimmers (t(273)=-2.643, p=0.009). From the age of 14, top-elite swimmers performed better than sub-elite swimmers (t(6.169)=-3.516, p=0.012). From the age of 18, top-elite swimmers performed better than elite swimmers(t(909)=-2.051, p=0.041).

For females, there was a significant effect of best performance group on rSBT from age 12 till 24 (p <0.05). Planned comparisons between the top-elite performance group and other performance groups revealed that from the age of 12, top-elite swimmers performed better high-competitive swimmers (t(430)=-4.034, p <0.001) and sub-elite (t(430)=-2.268, p=0.024). From the age of 14, top-elite swimmers performed better than elite swimmers (t(939)=-3.574, p <0.001).

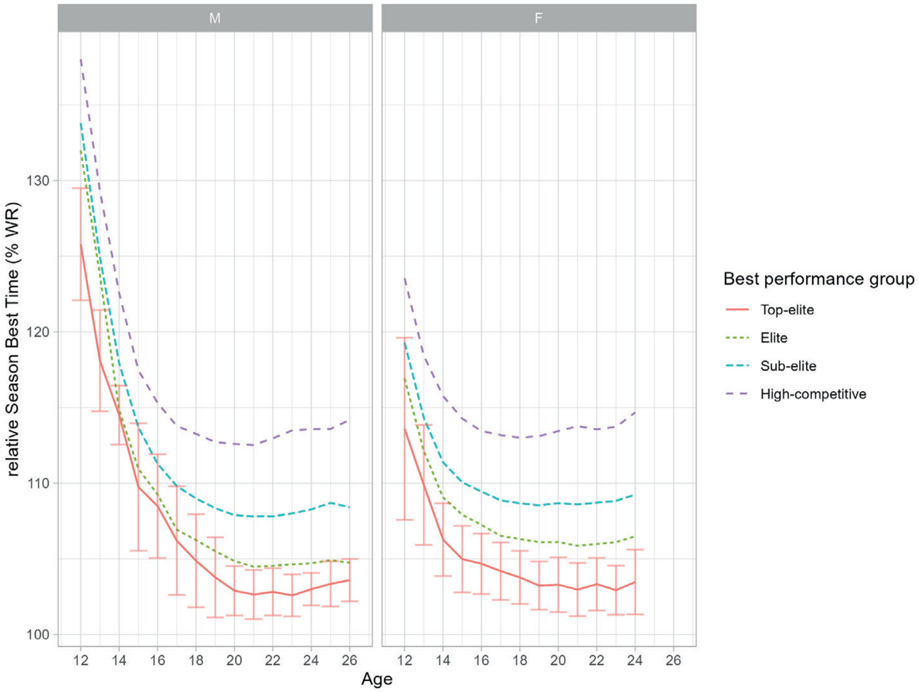

Figure 1. Performance development of male (left) and female (right) swimmers on the 100m freestyle from age 12 to 26 years specified for each of the four best performance groups

The stages towards acquisition of top-elite performance level

Figure 2 shows the first entry age per performance level of male and female top-elite swimmers. In other words, it presents the distribution in age categories at which male and female top-elite swimmers for the first time performed high-competitive, sub-elite, elite and top-elite level.

For males, the first entry age in high-competitive level ranges between 14 and 18 years, in which the majority of the male top-elite swimmers entered high-competitive level at the age of 16. The first entry age of sub-elite level ranges between the 15 and 21 years. At least one male swimmer who reached top-elite level, started participating at the sub-elite level for the very first time at the age of 15, while at least one other top-elite swimmer was 21. The age ranges of sub-elite level are largely similar to the age ranges at elite level, however the age at which the majority of male top-elite swimmers started to perform at elite level (20 years), is fairly higher than the age at which the majority of male top-elite swimmers started to perform at sub-elite and high-competitive level (both 16 years). Top-elite level performances started from the age of 17 years on, in which at least one male swimmer entered top-elite level for the first time at 24 years old. The majority of males entered top-elite level around the age of 21.

For females, the first entry age in high-competitive level ranges between the 12 and 14 years, in which the majority of female top-elite swimmers entered high-competitive level at the age of 13. This is about three years earlier than their male counterparts. The first age of sub-elite level ranges between the 12 and 16 years. The majority of the female top-elite swimmers reached sub-elite level for the first time when they were 15 years. The first female top-elite swimmer entered elite level when she was 13 years, however the majority started to perform at elite level at the age of 15. As in male top-elite swimmers, at least one female top-elite swimmer reached elite-level when she was 22 years. The range of first entry ages in female top-elite swimmers is widely spread at top-elite level. The first female top-elite level swimmer who entered top-elite level was only 14 years, however at least one female top-elite swimmer reached elite-level when she was 24 years. In between, no clear pattern was found for the majority of the swimmers.

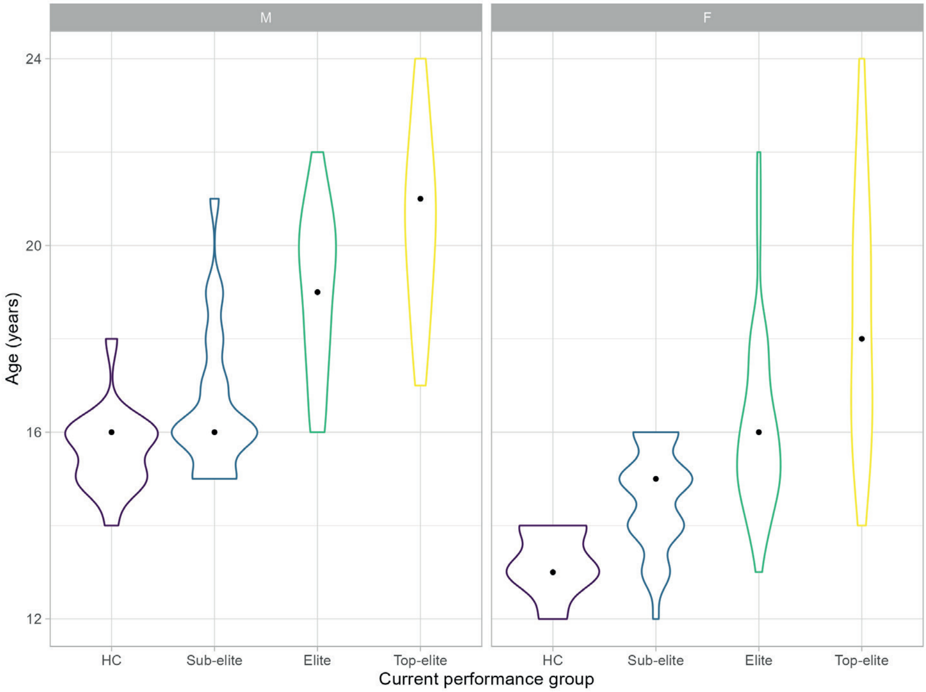

Figure 2. The distribution in age categories at which male (N=29) and female (N=57) top-elite swimmers for the first time performed at high-competitive (HC), sub-elite, elite and top-elite level. Dots represent mean ages.

2

Discussion

The present study investigated the 100m freestyle performance development longitudinally (over at least 5 years) in a multigenerational (over more than 20 years) sample of competitive swimmers to provide unique insight into the junior towards senior performance development of those few who reached top-elite level. The main findings showed that (1) from 12 years on, top-elite swimmers progressively outperformed swimmers of similar age, and that (2) there is a wide variety in the age at which male and female top-elite swimmers start to perform at high competitive, sub-elite, elite and top-elite level.

The findings of the present study concretize that successful performance development to the top is characterized by a high level of expertise from 12 years on. Male top-elite swimmers outperformed high-competitive swimmers from 12 years on, sub-elite swimmers from 14 years on and elite swimmers from 18 years, while female top-elite swimmers outperformed high-competitive and sub-elite swimmers from 12 years on and elite swimmers from 14 years on. This progressive trend not only characterizes the differences between performance groups, but also the variety within the top-elite performance group. For both male and female top-elite swimmers, it seems that the higher the performance level becomes, the more variety in the first entry age range exists. For example in female top-elite swimmers, the first entry age range expanded from two years (12-14 years) in high competitive level to ten years (14-24 years) at top-elite level. This means that at least one 14 year old female top-elite swimmer entered high-competitive level while at least one other female top-elite swimmer achieved at the same age top-elite level. Looking at the differences between male and female top-elite swimmers, we see that most of the female top-elite swimmers achieved the high-competitive, sub-elite, elite and top-elite level at a younger age compared to most of the male top-elite swimmers. For example, most female top-elite swimmers reached high-competitive level at the age of 13 whilst most male top-elite swimmers reached high-competitive level at the age of 16. Together, these results point out crucial differences in the individual pathways of performance development towards top-elite level within and between male and female swimmers.

Now, an intriguing question is which underlying performance characteristics (e.g. anthropometrical, technical, tactical, physiological and psychological characteristics) contribute to the successful performance development towards top-elite level. In here, it is important to consider that the underlying performance characteristics are influenced by maturation, learning and training (Elferink-Gemser & Visscher, 2012; Barbosa et al., 2015; Till et al., 2014) and that athletes always develop in and with their environment. The environment (e.g. parents, coaches, talent development programs, competition and training facilities) plays a crucial role in developing the underlying performance characteristics (Bloom, 1985; Phillips et al., 2010). For example, the popularity of a sport might influence national, regional and local selection procedures for talent identification and development programs and the level of competition. Individual differences in underlying performance characteristics, environmental characteristics, timing and tempo of the growth spurt and the number and quality of training hours may harness possible explanations for differences in swim performance between performance groups and sexes and for the wide variation in developmental patterns between top-elite swimmers. Therefore, future, longitudinal studies following youth swimmers throughout their sports career, measuring underlying performance characteristics, mapping environmental characteristics and tracking their maturation, learning, training and level of swim performance, could potentially provide further insight into successful 100m freestyle performance development of top-elite swimmers (Elferink-Gemser et al., 2011; Kannekens et al., 2011). In here, the effect of age of selection on the performance development of those reaching top-elite level should be addressed as well.

The present study is the first that investigated 100m freestyle performance development at such large scale. Following the method developed by Stoter et al. (2019), the present study defined swim performance as a relative measure instead of an absolute measure. The major strength of using a relative measure of swim performance (rSBT) is that it allows a more “fair” comparison of swim performance between and within swimmers. Therefore we were able to include swim performance over multiple generations which resulted in a big data set with multigenerational and longitudinal data. Consequently, we extended group sizes of populations characterized with smaller sample sizes (e.g. top-elite swimmers). This provided us the unique opportunity to investigate 100m freestyle performance development of top-elite, elite, sub-elite and high-competitive swimmers over more than 20 years. In a similar way, other sports with absolute performance measures (i.e. time-trial sports such as cycling or running) can be studied. However, when applying this method it is important to realize that a different classification of performance groups may lead to different outcomes (Swann et al., 2015). Hence, the present study carefully considered the definitions of top-elite, elite, sub-elite and high-competitive swimmers and defined performance groups based on task- and sex-specific limits, meaningful for the sport for competitive swimming.

With particular interest, the present study researched the performance development of top-elite swimmers. In here, the sport science perspective of striving to find regularities and patterns that can be applied to a whole population (Leezenberg & de Vries, 2001) was mixed with the investigation of individual pathways, a highly relevant and valuable combination for research in elite sports since experts in sports are individuals who do not comply with regularities. The frequency analysis on the first entry age of top-elite swimmers at the four performance levels showed an innovative method to describe the individual pathways towards acquisition of top-elite performance level. By analyzing these individual pathways, we gathered insight into the mean age and general age ranges at which top-elite swimmers for the first time started to perform at high-competitive, sub-elite, elite and top-elite level.

Consequently, the results demarcate age categories in which high-competitive, sub-elite, elite level have been achieved in order to successfully continue towards top-elite level.

From this study, we draw two conclusions. First, the results mark the important developmental stages of male and female top-elite swimmers by comparing their general level of performance with other performance groups. Top-elite swimmers are characterized by a high performance level from 12 years on and progressively outperform swimmers from similar age. However, this goes together with a large variety in the individual pathways towards top-elite level within and between sexes. Second, at a methodological level, the present study successfully applied the method of Stoter et al. (2019) and introduced an additional analysis that provided detailed insight about the age at which high-competitive, sub-elite, elite level was reached in order to make it to top-elite level in competitive swimming. This has the potential to be applied in other time-trial sports.

Perspective

The present study provides highly relevant and valuable information about the 100m freestyle performance development of male and female top-elite swimmers. The general developmental patterns and the first entry ages per performance level of male and female top-elite swimmers may function as guideline for coaches with athletes who are aiming to reach the top. With the results of this study, swimmers and coaches may get a better indication about which performance level at a certain age-range seems to be required to develop towards top-elite level. This may help swimmers and coaches in monitoring swim performance and setting realistic short and long-term goals. The paramount differences within and between the performance development of male and female top-elite swimmers underline the importance of a personalized approach and may have important implications on future training and athlete development programs. A next step to take is to longitudinally study the underlying performance and environmental characteristics leading to top-elite swim performance.

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Appendices

Appendix A. Mean and SD for rSBT per age, per best performance group of male swimmers.

Age	Best performance group	N	Mean ± SD
12	Top-elite	3	125.8 ± 3.7
12	Elite	7	132.0 ± 4.3
12	Sub-elite	69	133.8 ± 8.1
12	High-competitive	199	138.0 ± 8.0*
13	Top-elite	4	118.1 ± 3.3
13	Elite	10	123.7 ± 8.2
13	Sub-elite	93	124.9 ± 7.3
13	High-competitive	238	129.3 ± 7.5*
14	Top-elite	5	114.5 ± 2.0
14	Elite	17	114.8 ± 5.2
14	Sub-elite	128	117.9 ± 4.9*
14	High-competitive	308	122.6 ± 5.5*
15	Top-elite	13	109.8 ± 4.2
15	Elite	27	111.0 ± 4.8
15	Sub-elite	200	113.7 ± 3.8*
15	High-competitive	421	117.5 ± 3.8*
16	Top-elite	24	108.5 ± 3.4
16	Elite	53	109.2 ± 3.2
16	Sub-elite	306	111.3 ± 3.1*
16	High-competitive	577	115.3 ± 3.1*
17	Top-elite	24	106.2 ± 3.6
17	Elite	51	106.9 ± 2.4
17	Sub-elite	294	109.8 ± 2.8*
17	High-competitive	577	113.8 ± 2.9*
18	Top-elite	23	104.9 ± 3.1
18	Elite	53	106.2 ± 2.5*
18	Sub-elite	291	109.0 ± 2.6*
18	High-competitive	546	113.3 ± 2.7*
19	Top-elite	23	103.8 ± 2.6
19	Elite	48	105.5 ± 2.3*
19	Sub-elite	288	108.4 ± 2.2*
19	High-competitive	562	112.7 ± 2.4*
20	Top-elite	25	102.9 ± 1.6
20	Elite	54	104.9 ± 1.6*
20	Sub-elite	314	107.9 ± 2.1*
20	High-competitive	556	112.6 ± 2.5*
21	Top-elite	25	102.6 ± 1.6

Age	Best performance group	N	Mean ± SD
21	Elite	55	104.5 ± 1.3*
21	Sub-elite	335	107.8 ± 1.9*
21	High-competitive	579	112.5 ± 2.5*
22	Top-elite	26	102.8 ± 1.6
22	Elite	57	104.5 ± 1.6*
22	Sub-elite	352	107.8 ± 1.9*
22	High-competitive	634	113.0 ± 2.8*
23	Top-elite	24	102.6 ± 1.4
23	Elite	50	104.6 ± 1.3*
23	Sub-elite	240	108.0 ± 2.5*
23	High-competitive	394	113.5 ± 3.0*
24	Top-elite	21	103.0 ± 1.1
24	Elite	40	104.7 ± 1.3*
24	Sub-elite	178	108.3 ± 2.5*
24	High-competitive	255	113.6 ± 2.8*
25	Top-elite	18	103.3 ± 1.5
25	Elite	34	104.9 ± 2.0*
25	Sub-elite	109	108.7 ± 3.1*
25	High-competitive	126	113.6 ± 2.4*
26	Top-elite	16	103.6 ± 1.4
26	Elite	26	104.7 ± 2.1*
26	Sub-elite	68	108.4 ± 2.1*
26	High-competitive	87	114.2 ± 3.1*

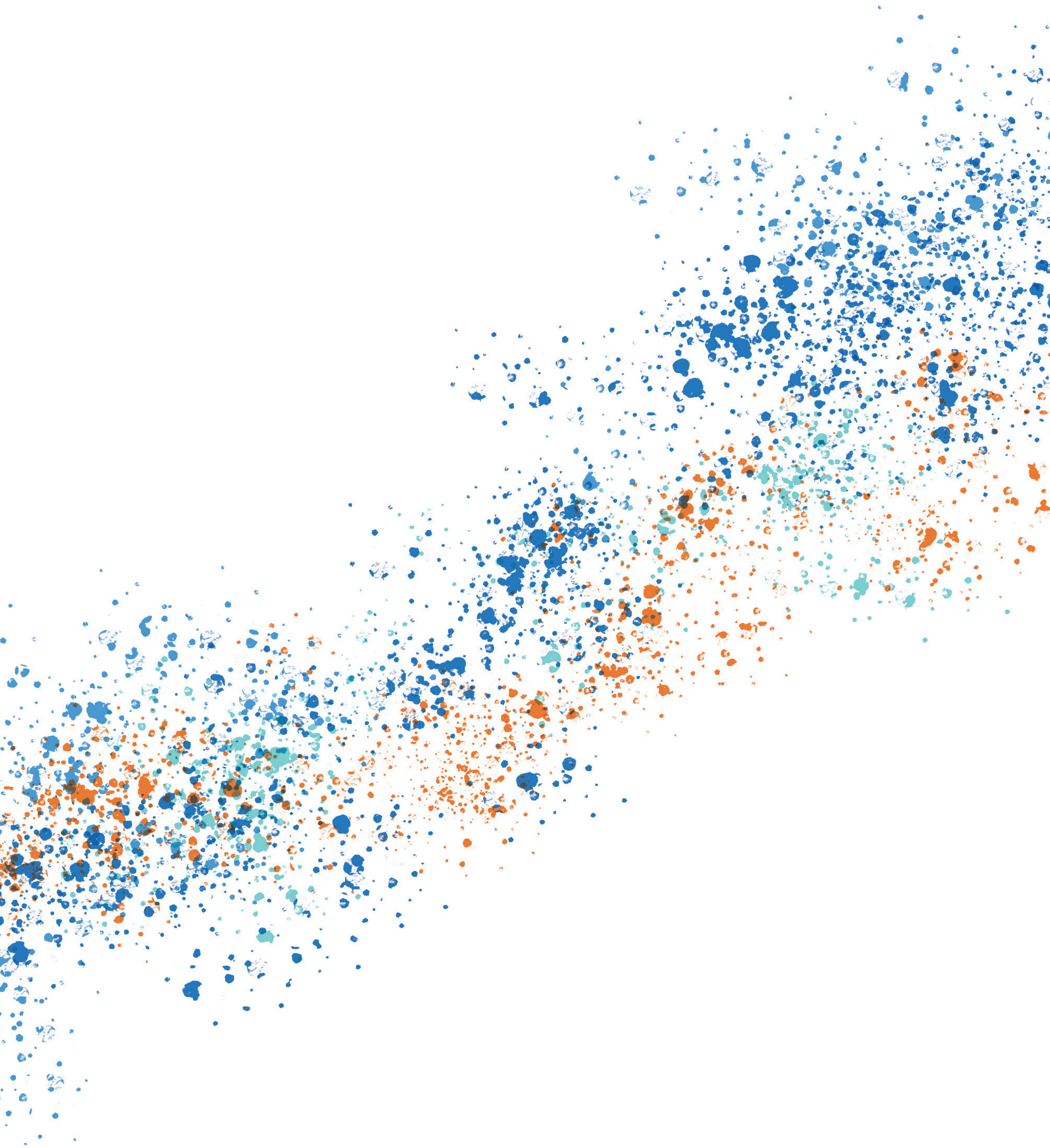
Note. * indicates significant difference between top-elite performance group, $p < 0.05$.

Appendix B. Mean and SD for rSBT per age, per best performance group of female swimmers.

Age	Best performance group	N	Mean ± SD
12	Top-elite	6	113.6 ± 6.0
12	Elite	41	116.9 ± 5.3
12	Sub-elite	83	119.3 ± 5.5*
12	High-competitive	306	123.5 ± 6.2*
13	Top-elite	14	109.9 ± 4.0
13	Elite	70	112.1 ± 4.9
13	Sub-elite	122	114.3 ± 4.2*
13	High-competitive	458	118.4 ± 4.7*
14	Top-elite	26	106.3 ± 2.4
14	Elite	95	109.1 ± 3.5*
14	Sub-elite	190	111.4 ± 3.3*
14	High-competitive	635	115.8 ± 3.6*
15	Top-elite	43	105.0 ± 2.2
15	Elite	150	107.9 ± 2.7*

Age	Best performance group	N	Mean ± SD
15	Sub-elite	263	110.1 ± 3.0*
15	High-competitive	791	114.3 ± 3.1*
16	Top-elite	52	104.7 ± 2.0
16	Elite	186	107.2 ± 2.3*
16	Sub-elite	295	109.4 ± 2.7*
16	High-competitive	901	113.4 ± 2.7*
17	Top-elite	54	104.2 ± 1.9
17	Elite	179	106.5 ± 1.8*
17	Sub-elite	298	108.9 ± 2.1*
17	High-competitive	877	113.2 ± 2.7*
18	Top-elite	51	103.8 ± 1.8
18	Elite	171	106.3 ± 1.6*
18	Sub-elite	292	108.7 ± 2.0*
18	High-competitive	824	113.0 ± 2.5*
19	Top-elite	49	103.2 ± 1.6
19	Elite	167	106.1 ± 1.8*
19	Sub-elite	292	108.5 ± 1.9*
19	High-competitive	832	113.1 ± 2.6*
20	Top-elite	51	103.3 ± 1.8
20	Elite	182	106.1 ± 1.9*
20	Sub-elite	312	108.7 ± 2.1*
20	High-competitive	912	113.4 ± 2.9*
21	Top-elite	45	103.0 ± 1.8
21	Elite	159	105.9 ± 1.7*
21	Sub-elite	251	108.6 ± 2.0*
21	High-competitive	626	113.8 ± 3.2*
22	Top-elite	44	103.3 ± 1.7
22	Elite	142	106.0 ± 1.8*
22	Sub-elite	175	108.7 ± 1.9*
22	High-competitive	322	113.6 ± 3.0*
23	Top-elite	37	102.9 ± 1.6
23	Elite	106	106.1 ± 2.1*
23	Sub-elite	123	108.8 ± 2.1*
23	High-competitive	189	113.7 ± 3.2*
24	Top-elite	32	103.5 ± 2.1
24	Elite	86	106.5 ± 1.8*
24	Sub-elite	90	109.2 ± 2.3*
24	High-competitive	133	114.7 ± 3.4*

Note. * indicates significant difference between top-elite performance group, $p < 0.05$.



Chapter 3

Interim Performance Progression (IPP) during consecutive season best performances of talented swimmers

Post, A. K., Koning, R. H., Stoter, I. K., Visscher, C., & Elferink-Gemser, M. T. (2020). Interim Performance Progression (IPP) During Consecutive Season Best Performances of Talented Swimmers. *Frontiers in Sports and Active Living, 2*, [579008]. https://doi.org/10.3389/fspor.2020.579008

Abstract

Objective

The main goal of the present study was to investigate the interim performance progression (IPP) of talented swimmers. Part of this group ultimately made it to the top (referred to as elite swimmers) whereas others did not make it to the top (referred to as high-competitive swimmers). Rather than investigating performance progression based solely on season best performances, we included the first swim performance of the season in the metrics of IPP. Knowledge about the IPP of talented swimmers from and towards their season best performances relative to the first swim performance of the season will enhance our understanding of changes in season best performances during the talent trajectory and provide valuable insights for talent development and selection processes in competitive swimming.

Methods

15,944 swim performances (first swim performances of the season and season best performances) between 1993-2019 of 3,199 talented swimmers (of whom 556 reached elite level and 2,643 reached high-competitive level) were collected from Swimrankings and related to the prevailing world record of the corresponding sex. The pattern of IPP was represented by two phases: phase A and phase B. Phase A reflected the performance progression between the previous season best performance and the first swim performance of the current season (PP_A) and phase B reflected the performance progression between the first swim performance of the current season and the season best performance of the current season (PP_B). Depending on the normality check, we used independent sample t-tests or Mann Whitney tests to establish significant differences in PP_A and PP_B between elite and high competitive swimmers per age category per sex ($p < 0.05$).

Results

Without denying individual differences, male elite swimmers improved more during phase B from age 15 till 24 compared to high-competitive swimmers (20.5% vs. 13.1% respectively, $p < 0.05$). Female elite swimmers improved more during phase B from age 13 till 23 compared to high-competitive swimmers (21.1% vs. 14.6% respectively, $p < 0.05$). Except for age 14 in males, there were no significant differences between performance groups in PP_A.

Conclusion

Talented swimmers who ultimately made it to the top (elite swimmers) are characterized with different patterns of IPP compared to talented swimmers who did not make it to the top (high-competitive swimmers). After puberty, elite and high-competitive swimmers performed in general ~1% slower at the start of their season compared to their previous season best performance (PP_A). However, elite swimmers improved more in the period between their first swim performance of the season and their season best performance (PP_B) from age 13 (females) and age 15 (males) onwards.

Keywords

Swimming, acquisition of expertise, performance progression analysis, elite athletes, talent development

Introduction

For coaches and stakeholders in competitive swimming, season best performances and national rankings are the main information source for talent identification and selection processes (KNZB). Based on this information and their perception about how that information relates to future performance, they have to make decisions about whether or not a swimmer is selected for an athlete development program (Schorer et al., 2017). However, several researchers are questioning this one-sided approach in which performance at early stages of development (e.g. age 12 onwards in competitive swimming; KNZB, 2018) is used as an indicator of future performance (Abbott et al., 2005; Vaeyens et al., 2009; Elferink-Gemser et al., 2011). They advocate that there are multiple pathways to reach expertise and that there is a risk to erroneously overlook athletes as being talented by focusing on current performance only (Vaeyens et al., 2008; Gulbin et al., 2013; Till et al., 2016).

In order to provide scientific-based knowledge about the value of early age performance in competitive swimming, Post et al., (2020) tracked down the junior-to-senior performance development of top-elite swimmers at the 100m freestyle event. This research was based on the analysis of season best performances and provided support for both perspectives. The findings showed that 1) compared to each other, top-elite swimmers follow unique individual developmental pathways towards expertise and 2) compared to other performance groups, top-elite swimmers in general progressively outperform their elite, sub-elite and high-competitive swimmers of similar age from twelve years onwards.

In addition to examining group averages as in the research of Post et al. (2020), upper and lower limits of swimmers who have made it to the top can provide relevant insights as well. Stoter et al. (2019) used the upper limits of elite speed skating performance (slowest performance per age and per sex for those who later reached the elite level in this sport) to define performance benchmarks for future speed skaters. The results showed that the majority of talented male and female speed skaters who performed within the elite benchmarks at a younger age, did not make it to the top. These findings combined with previous results of Post et al. (2020) inspire to continue the investigation of youth performance. What characterizes the performance development of those who are considered as talented swimmers (e.g. perform within performance benchmarks) and do reach the top compared to their talented counter peers who do not reach the top?

Probably, the answer to this question may not be hidden in solely tracking season best performances. Although monitoring and modelling season best performances highly contributed to a deeper understanding of performance development to the swimming top (Stewart & Hopkins, 2000; Costa et al., 2011; Allen et al., 2014; König et al., 2014; Post et al., 2020; Yustrus et al., 2020), it would be interesting to include additional swim performances in mapping performance progression of talented swimmers. As such, scientific-based data about 1) the progression between a swimmer's previous season best performance and his first swim performances of the season and 2) the progression between a swimmer's first swim performance of the season and his current season best performance, could provide meaningful information about the interim performance progression (IPP) during two consecutive season best performances.

Knowledge about IPP during consecutive season best performances of talented swimmers would enhance our understanding of changes in season best performances during the talent trajectory. In particular, this is the case when IPP is investigated from a retrospective perspective in which talented swimmers who made it to the top (elite swimmers) are compared to their talented counter peers who in the end did not make it to the top (high-competitive swimmers). In here, a longitudinal approach is necessary as the road to the top is long and often combined with large inter-individual differences between swimmers due to processes of growth and maturation (Kannekens et al., 2011; Malina et al., 2015; Elferink-Gemser et al., 2018). This would provide valuable and additional insights about the general and individual performance patterns of swimmers on their way to the top, which can be used to optimize talent development programs. As such, federations, coaches and swimmers would benefit from a more detailed guideline towards elite swimming performances and be able to set and monitor realistic and data-driven goals about the development of swim performances during a swimming season. Moreover, IPP may be an additional variable to select and monitor swimmers who have the potential to make it to the top.

However, to the best of our knowledge, a longitudinal, retrospective analysis of IPP of talented swimmers with the potential to make it to the elite level has not been conducted yet. Therefore, the main goal of this study was to longitudinally and retrospectively investigate the IPP during consecutive season best performances of talented swimmers. Part of this group ultimately made it to the top (referred to as elite swimmers) whereas others did not make it to the top (referred to as high-competitive swimmers). Given the fact that at some point during their career, elite swimmers outperformed their peers, we hypothesize that elite swimmers have higher IPP compared to swimmers who did not reach elite level (high-competitive swimmers).

Materials and methods

Ethical approval

All procedures used in the study were approved by the Local Ethical Committee of the University Medical Center Groningen, University of Groningen, The Netherlands (201900334) in the spirit of the Helsinki Declaration with a waiver of the requirement for informed consent of the participants given the fact that the study involved the analysis of publicly available data.

Data collection

The swimmers we selected for this study were international male and female swimmers with performance data on the 100m freestyle long course event. We chose this event because it is considered as the key distance in competitive swimming. It has been on the Olympic program since 1904 (men) and 1912 (women) and is characterized with the largest number of world-wide participants. Moreover competition starts from an early age on and the word-wide competition level is high for both male and female swimmers (FINA, 2019; Swimrankings, 2019).

Performance data (in terms of swim times) was obtained from Swimrankings (2019), a recognized public data source which records international swimming race results. Performance data were collected from 88 countries across different parts of the world including Africa, America, Asia, Australia and Europe. We collected all available 100m freestyle long course results from Swimrankings' database, which initially resulted in 2,864,4481 observations between 1993 and 2019.

Data processing

For the purpose of the present study, we transformed the structure of the dataset. Starting with individual competition observations (each observation e.g. swim performance stored into a unique row), we restructured the dataset in individual season observations (two observations e.g. swim performances stored in one row). The two observations we stored in one row were the first swim performance of the swimming season and the best swim performance of the swimming season. All other performance data within the season were discarded from further analysis.

Performance data from the 1st of January 2008 till the 1st of January 2010 were excluded from analysis (we exclude full-body polyurethane swimsuits (Toussaint et al., 2002; Tiozzo et al., 2009; Tomikawa and Nomura, 2009). Swim performances over 180 seconds were excluded from analysis to ensure a representative dataset. Based on swim dates, performance data were classified in swimming seasons. Each swimming season officially starts on the 1st of September of a calendar year and ends on the 31st of August of the next calendar year (FINA, 2019). Swimmers were classified in age categories based on their age on the 31st of December of the swimming season (KNZB, 2018). Therefore, all ages mentioned in the present study refer to the age category in which a swimmer participated during the swimming season and not the calendar age of the swimmer.

Defining swim performance and performance groups

The present study includes swim performances of multiple generations, necessitating the correction of evolution in a given sport (Stoter et al., 2019; Post et al., 2020). The method we used to correct for the evolution in competitive swimming was introduced by Stoter et al. (2019) in the sport of speed skating and later successfully used by Post et al. (2020) in the sport of competitive swimming. Swim performances were related to the prevailing world record (WR) or the fastest time in textile of the corresponding sex. The prevailing WR is the official WR at the date the swimmer performed the swim time. WRs from 2008 or 2009 were replaced by the prevailing fastest time in textile. The corrected swim time will be referred to as relative Swim Time (rST) and is presented as a percentage of the world record or fastest time in textile. In this study, rST defines swim performance (see equation 1).

$$\text{relative swim time (rST)} = \left(\frac{\text{swim time}}{\text{world record}}\right) * 100\% \qquad \text{(eq. 1)}$$

Two performance levels were defined: elite and high-competitive. Each performance level was characterized by sex-specific limits to account for differences in competition level between males and females (see Table 1). The limits were calculated as the mean of 5 season best rST's for the 50th swimmer from either the 100m freestyle performance FINA World Ranking Lists of 2015-2019 (FINA, 2019) or the 100m freestyle performance National Ranking Lists of the Netherlands 2015-2019 (Swimrankings, 2019). The limits of the elite performance level were equal to the average of the season best rST's of the 50th male and female swimmer of the FINA World Ranking List 2015-2019. The limits of the high-competitive level were defined so that they represented the 50th male and female swimmer of the National Ranking List of the Netherlands.

We determined each swimmer's best performance group by allocating the best rST ever to one of the two performance levels, meaning that a swimmer either once or multiple times has reached this performance level at any age. For example, if a male swimmer has a best rST of 109.0%, his best performance level corresponds with the limits of the high-competitive performance group. Swimmers with a best rST ever outside the limits of the high competitive level (best rST >114.0% for males and best rST > 115.1% for females) were excluded from further analysis.

Inclusion criteria

We included talented swimmers of which some swimmers ultimately made it to the top (elite swimmers) and others did not (high-competitive swimmers). The inclusion criteria were: (1) swimmers who had at least one swim performance in the age category of 22 years or older (males) or 20 years or older (females). Based on research of Allen et al. (2014), we suggest that this is in general the expected minimum age for swimmers to achieve their career best performances. To ensure a dataset representing the developmental pathway towards peak performance, we solely included (2) swim performances up to and including the swimmer's career best swim performance. Furthermore we selected only those swimmers who (3) where between the 12 and 24 years old; (4) had performance data of at least two consecutive swimming seasons (5) had two observations within a swimming season and (6) had season best rST's within the performance benchmarks.

The performance benchmarks were taken as indicator for future performances towards elite level swimming. Therefore swimmers performing within these performance benchmarks were in the present study considered as talented swimmers. The performance benchmarks were based on previous research of Post et al. (2020) and reflect the maximal season best rST for elite swimmers per age and per sex (see **Appendix A**). Performance benchmarks were set to be monotone, meaning that with every successive maximal season best rST lower than the previous, the benchmark will decrease towards the value of this season best rST, but with every successive maximal season best rST higher than the previous, the benchmark will remain at the same value.

Table 1 represents the male/female distribution and the number of observations (i.e. total rSTs) for each performance group included for analysis, with an average of 3.6 ± 2.0 observations per swimmer.

Table 1. Total number of swimmers (N = 3,199) and observations (N =8,005) for each performance group specified by sex for the analysis on within-season performance progression (WSPP).

	Males		**Females**	
	Individuals	*Observations*	*Individuals*	*Observations*
Elite	196	638	360	1,062
High-competitive	1,279	3,085	1,364	3,220

Note. Elite males: best rST ≤ 103.9%; Elite females: best rST ≤ 105.8%; High-competitive males: 103.9% < best rST ≤ 114.0%; High-competitve females: 105.8% < best rST ≤ 115.1%.

Defining within-season performance progression (WSPP)

The concept of interim performance progression (IPP) is explained as the pattern of performance progression during two consecutive seasons relative to a common reference point. Therefore, the pattern of IPP is described by two phases: phase A and phase B.

Phase A is presented as the period between the previous season best rsT and the first swim performance of the current season (first rST). Phase B is presented as the period between the first rST and the current season best rST. So, the first rST is the common reference point in phase A and phase B (see Figure 1). The first rST can be worse, the same or better than the previous season rST. In Figure 1, it is shown as worse. The current season best rST can be the same or better than the first rST. In Figure 1, it is shown as better. Ultimately, the current season best rST can be the worse, the same or better than the previous season best rST. In **Figure 1**, it is shown as better.

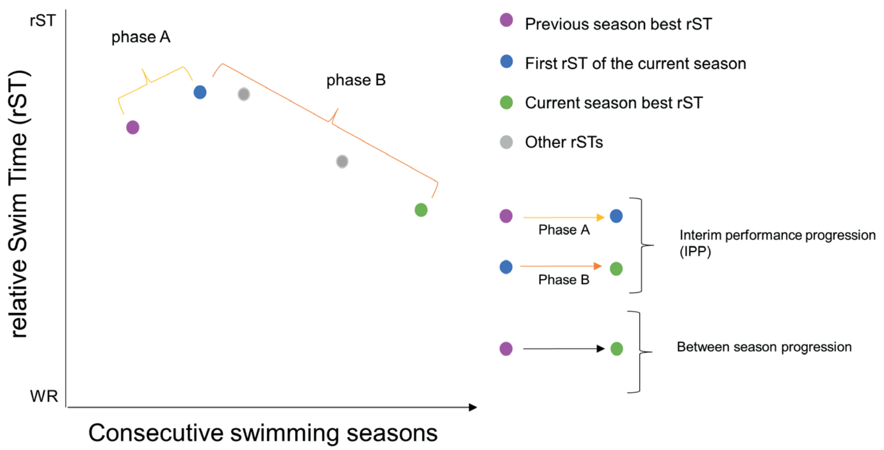


Figure 1. The concept of interim performance progression (IPP).

The performance progression during phase A (PP_A) is defined as the percentage of the first rST relative to the previous season best rST (see equation 2). This measure is constructed to reflect the start level of a swimmer relative to his best swim performance of the previous season. An outcome below the 100% means that the swimmer was faster than his previous season best rST (improved) and an outcome above the 100% means that the swimmer was slower than his previous season best rST (deteriorated). An outcome of 100% means that the swimmer is at the exact same level as his previous season best rST (stabilized).

$$PP_A = \left(\frac{\text{first rST}}{\text{previous season best rST}}\right) * 100\% \qquad \text{(eq. 2)}$$

The performance progression during phase B (PP_B) is defined as the percentage change a swimmer has moved towards the prevailing world record (see equation 3). In other words, PP_B is relative to the gap a swimmer needs to close in order to break the prevailing world record. PP_B reflects the difference between the best rST of the current season (current season best rST) and the first rST divided by the difference between the first rST and the prevailing world record or fastest time in textile (see equation 3).

A positive outcome indicated that a swimmer has moved towards the prevailing world record and improved relative to his first rST. An outcome of 0% indicated that the swimmer's gap to the world record stayed the same and that the swimmer did not improve relative to his first rST.

$$PP_B = -\left(\frac{\text{current season best rST} - \text{first rST}}{\text{first rST} - 100}\right) * 100\% \qquad \text{(eq. 3)}$$

As an example, we illustrate the pattern of IPP of a fictive swimmer with a season best rST of 106.5 in the previous season (2016/2017), a first rST of 107.6% in the current season (2017/2018) and a season best rST of 106.0% in the current season (2017/2018). His PP_A will be (107.6 (first rST) / 106.5 (previous season best rST)) * 100%. In short his PP_A is (107.6 / 106.5) * 100% = 101.0%. An outcome above the 100% means that the swimmer's SL is slower than his best rST of the previous season. His PP_B will be – (106.0 (current season best rST) -107.6 (first rST)) / 107.6 (first rST) – 100%. In short his PP_B is –(-1.6) / 7.6 *100 = 21%. A positive outcome indicates the swimmer moved towards the prevailing world record and that he improved his swim performance between the start of the current season and the moment he swum his best rST of the current season. The pattern of IPP of this fictive swimmer is characterized by a small decrease in phase A (1% above his previous attained performance level), followed by an increase during phase B.

Statistical analysis

All data were analyzed for male and female swimmers separately using IBM SPSS Statistics 24 and R (R Core Team, 2019) (R version 3.6.0). Mean scores and standard deviations were calculated for swim performance (previous season best rST, first rST and current season best rST), performance progression in phase A (PP_A) and performance progression in phase B (PP_B) for the two performance groups per age category (**see Appendix B and C**). The normality of the distributions was assumed for n >30, according to the central limit theorem (Field, 1993). For n<30, distributions were visually inspected by histograms and Q-Q plots. Per age category, an independent-samples t-test (normality assumed) or Mann-Whitney test (normality violated) was conducted to compare PP_A en PP_B between elite and high-competitive swimmers. To interpret the scores, effect sizes (r of *d*, depending on normality) were calculated. An effect size of approximately 0.20 (*d*) or 0.10 (r) was considered small, 0.50 (*d*) or 0.30 (r) moderate and 0.80 (*d*) or 0.50 (r) large (Cohen, 1988). Statistical tests were executed for the age categories in which there were more than six observations in the elite performance group. For all tests, $p < 0.05$ was set as significance.

Results

Figures 2 and 3 illustrate the performance progression in phase A (PP_A) and phase B (PP_B) respectively of talented male and female swimmers on the 100m freestyle from age 14 to 24 (males) and 12 to 22 (females). Within each age category, all swimmers performed within the corresponding performance benchmarks, however part of them reached the top (elite swimmers) and part of them did not reach the top (high-competitive swimmers). The average period of PP_A was 252 ± 87 days and the average period of PP_B was 102 ± 76 days.

Except for age 14 in males, Mann-Whitney tests and independent sample t-tests showed no significant differences between elite and high-competitive swimmers in $PP_{A.}$

For males, we found significant differences in PP_B between elite and high-competitive swimmers from age 15 till 24 ($p < 0.05$). From age 15 onwards, male elite swimmers improved on average more in their swim performance than male high-competitive swimmers in the period between their first swim performance of the current season and their current season best performance.

For females, we found significant differences in PP_B between elite and high-competitive swimmers from age 13 till 22 ($p < 0.05$). From age 13 onwards, female elite swimmers improved on average more in their swim performance than female high-competitive swimmers in the period between their first swim performance of the current season and their current season best performance. Corresponding test statistics are reported in **Appendix D and E** (males and females respectively).

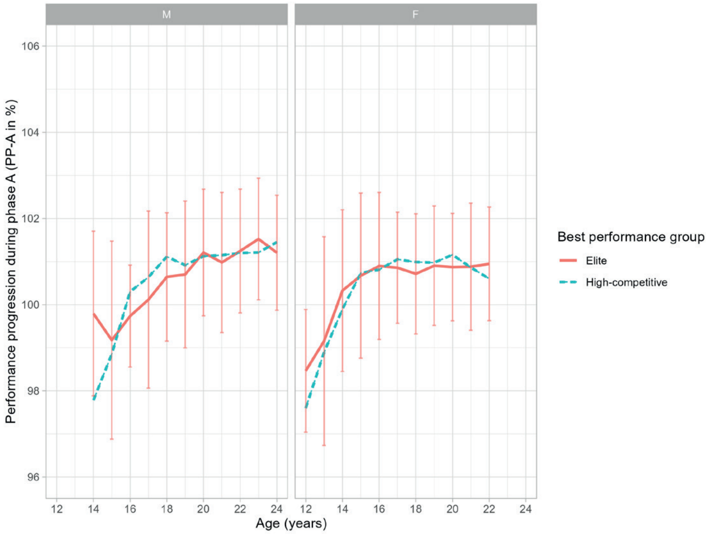


Figure 2. Performance progression in phase A (mean PP_A) of male and female elite and high-competitive swimmers. Scores above the 100% indicate that the first rST is slower compared to the previous season best rST. For the purpose of this study, SDs are only shown for elite swimmers.

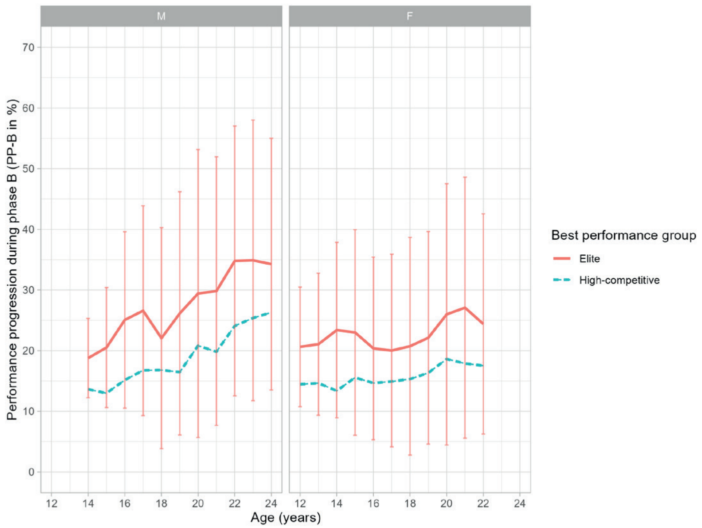


Figure 3. Performance progression in phase B (mean PP_B) of male (right) and female (left) elite and high-competitive swimmers on the 100m freestyle from age 12 to 24. Higher scores indicate higher progression. For the purpose of this study, SDs are only shown for elite swimmers.

Discussion

The present study investigated the in interim performance progression (IPP) during consecutive season best performances of talented swimmers. Part of this group ultimately made it to the top (referred to as elite swimmers) whereas others did not make it to the top (referred to as high-competitive swimmers). The main findings of this study showed that without denying individual differences 1) elite swimmers improved more in swim performance than high-competitive swimmers during phase B (the period between the first rST and the current season best rST) and that 2) there were no differences between elite and high-competitive swimmers in performance progression between the previous season best performance and the first swim performance of the current season (PP_A) (except for age 14 in males).

Considering these outcomes, it is important to notice that the results of the present study are inextricably linked to how we defined the metrics of IPP: PP_A and PP_B. As it is well known that at some point during a swimmers' career, the rate of performance progression begins to reduce (known as the principle of diminishing returns to training; Hoffman, 2014), we found it highly important to include metrics of IPP that enabled the interpretation of performance progression of swimmers relative to their previous performance level (PP_A) and relative to the elite performance level (PP_B). By relating performance progression to the gap a swimmer needs to close in order to break the world record, PP_B accounted for the principle of diminishing returns and related performance progression to the (prevailing) fastest male or female swimmer of the world. Together, this makes that PP_B can be compared between swimmers of different performance levels and generations and simultaneously can function as measure to point out how much a swimmer moved forward to the prevailing world record. In here, the present study aimed to make a more "fair" comparison between and within swimmers in a multigenerational and longitudinal dataset. To the best of our knowledge, the perspective on IPP and the related metrics of IPP have not been described in swimming literature yet.

Since IPP is explained as the pattern of performance progression during two consecutive seasons relative to a common reference point (first rST), the present study contributed to additional insights about the course of performance progression of talented swimmers. Descriptive statistics show that during puberty, talented male and female swimmers progress in the period between the previous season rST and the first rST (PP_A) and in the period between the first rST and the current season best rST (PP_B). In other words: they progressed in both phase A and phase B. However, post-puberty, progression during two consecutive season best performances generally took place in phase B rather than phase A. The latter suggests that coaches and swimmers should not get too discouraged if the first swim performance of the current season is ~1% slower compared to the previous season best performance.

As elite swimmers and high-competitive swimmers did not significantly differ in the performance progression in phase A (except for age 14 in males), we suggest that differences in PP_B between elite and high-competitive swimmers should not be accounted to previously emerged differences in PP_A, but to different developmental patterns in phase B. Obviously, an intriguing question is: what causes these differences in developmental patterns and the higher PP_B of elite swimmers? In here, it is interesting to consider the inter-individual differences in adolescent growth processes and the quantity and quality of training hours as explaining factors (Ericsson et al., 1993; Malina et al., 2015). Moreover, differences in underlying performance characteristics between elite and high-competitive swimmers might relate to a larger performance potential (Elferink-Gemser et al., 2011). If so, PP_B might be a promising variable for talent development and selection processes as it may reflect this larger performance potential. However, the present study did not include any of these factors and consequently, more research is warranted. Therefore, a recommendation for future research would be to further unravel successful performance development to the top by tracking maturation, learning and training related to the personal performance characteristics of the individual swimmers (e.g. between 12-18 years) and their environment over time (Jonker et al., 2010; Elferink-Gemser & Visscher 2012; Till et al., 2013). Moreover, as the present study showed large SDs within age categories and different effect sizes between age categories, it would be interesting to include multilevel modelling to examine within-subject variations and age-related effects in future studies investigating talented swimmers.

Conclusion

The present study showed significant differences in IPP between talented swimmers who have made it to the top (referred to as elite swimmers) and talented swimmers who did not make it to the top (referred to as high-competitive swimmers). Without denying individual differences, talented swimmers who have made it to the top, improved more in the period between the first swim performance of the season and their current season best performance (PP_B) than talented swimmers who did not make it to the top.

Practical implications

The findings of the present study can be used to compare interim performance progression (IPP) of talented swimmers nowadays with the age-related IPP of swimmers who have reached elite level. In this way, IPP might in addition to swim performance function as an additional tool for federations and coaches to further select and monitor future talented swimmers. However at all times, federations and coaches should be aware that performance progression is not a linear process and that there are different pathways to elite level performance. Therefore, we want to emphasize to use IPP as one of many parameters which can provide insight about performance progression of talented swimmers.

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Appendices

Appendix A. Performance benchmarks (%WR) for identifying talented swimmers based on the performance development of elite swimmers investigated in previous research of Post et al. (2020).

Age	Males	Females
12	138.4	130.9
13	136.1	130.4
14	125.8	130.4
15	125.8	123.3
16	120.3	118.6
17	115.8	118.6
18	113.9	113.2
19	113.9	113.2
20	110.3	113.1
21	110.3	110.1
22	108.4	110.1
23	107.8	109.0
24	107.3	109.0
25	105.7	107.8
26	105.7	105.7

Appendix B. Mean and SD for previous season best rST, first rST, current season rST, PP_A and PP_B, per age, per best performance group of male swimmers.

Age	*Best performance group*	*N*	*Previous season best rST*	*First rST*	*Current season rST*	*PP_A*	*PP_B*
14	Elite	7	118.8 ± 4.2	118.6 ± 4.9	114.9 ± 3.1	99.8 ± 1.9	18.8 ± 6.5
14	High-competitive	117	124.5 ± 5.2	121.7 ± 4.0	118.7 ± 3.7	97.8 ± 2.4*	13.6 ± 8.8
15	Elite	13	114.6 ± 5.1	113.6 ± 4.3	110.8 ± 3.5	99.2 ± 2.3	20.5 ± 9.9
15	High-competitive	260	119.8 ± 5.0	118.4 ± 4.3	115.9 ± 3.8	98.9 ± 2.3	13.0 ± 9.9*
16	Elite	22	109.8 ± 2.8	109.5 ± 2.7	107.0 ± 2.0	99.7 ± 1.2	25.1 ± 14.5
16	High-competitive	369	115.2 ± 3.6	115.5 ± 3.4	113.1 ± 3.1	100.3 ± 2.1	15.2 ± 12.1*
17	Elite	38	107.9 ± 2.4	108.0 ± 2.2	105.8 ± 1.9	100.1 ± 2.1	26.6 ± 17.3
17	High-competitive	452	112.9 ± 3.0	113.6 ± 2.9	111.2 ± 2.6	100.6 ± 2.0	16.7 ± 12.4*
18	Elite	61	106.4 ± 2.2	107.0 ± 2.4	105.4 ± 1.9	100.6 ± 1.5	22.1 ± 18.2
18	High-competitive	433	111.1 ± 2.7	112.3 ± 2.8	110.1 ± 2.3	101.1 ± 2.0	16.8 ± 12.8*
19	Elite	87	105.8 ± 2.1	106.6 ± 2.5	104.7 ± 1.9	100.7 ± 1.7	26.1 ± 20.0
19	High-competitive	451	110.8 ± 2.8	111.8 ± 3.0	109.7 ± 2.5	100.9 ± 1.8	16.5 ± 12.3*
20	Elite	93	104.9 ± 1.7	106.2 ± 2.0	104.3 ± 1.7	101.2 ± 1.5	29.4 ± 23.7
20	High-competitive	275	108.4 ± 1.9	109.6 ± 2.3	107.4 ± 1.6	101.1 ± 1.7	20.8 ± 14.8*
21	Elite	93	104.6 ± 1.4	105.7 ± 1.7	103.9 ± 1.4	101.0 ± 1.6	29.8 ± 22.1
21	High-competitive	273	108.2 ± 2.1	109.4 ± 2.3	107.4 ± 1.7	101.1 ± 1.7	19.8 ± 14.6*
22	Elite	73	104.5 ± 1.4	105.8 ± 1.9	103.7 ± 1.4	101.2 ± 1.4	34.8 ± 22.2
22	High-competitive	143	107.2 ± 1.5	108.5 ± 2.1	106.2 ± 1.2	101.2 ± 1.6	24.1 ± 15.5*
23	Elite	58	103.9 ± 1.3	105.5 ± 1.7	103.6 ± 1.5	101.5 ± 1.4	34.9 ± 23.1
23	High-competitive	98	106.9 ± 1.6	108.2 ± 1.8	105.9 ± 1.0	101.2 ± 1.6	25.4 ± 15.0*
24	Elite	38	104.2 ± 1.5	105.5 ± 1.3	103.5 ± 1.2	101.2 ± 1.3	34.3 ± 20.7
24	High-competitive	55	106.5 ± 1.3	108.0 ± 1.7	105.8 ± 1.0	101.5 ± 1.3	26.3 ± 14.1*

Note. * indicates significant difference (tested for PPa and PPb) between elite performance group, $p < 0.05$

Appendix C. Mean and SD for previous season best rST, first rST, current season rST, PP_A and PP_B, per age, per best performance group of female swimmers.

Age	Best performance group	N	Previous season best rST	First rST	Current season rST	PP_A	PP_B
12	Elite	7	120.3 ± 2.2	118.4 ± 2.0	114.6 ± 2.5	98.5 ± 1.4	20.6 ± 9.9
12	High-competitive	142	128.8 ± 7.7	125.5 ± 5.7	121.6 ± 4.4	97.6 ± 3.8	14.5 ± 11.1
13	Elite	22	115.1 ± 5.0	114.0 ± 4.2	111.0 ± 3.4	99.2 ± 2.4	21.1 ± 11.7
13	High-competitive	233	121.5 ± 4.7	120.1 ± 4.2	117.0 ± 3.6	98.9 ± 2.5	14.6 ± 10.1*
14	Elite	30	110.0 ± 3.6	110.3 ± 3.3	107.7 ± 2.3	100.3 ± 1.9	23.4 ± 14.5
14	High-competitive	389	117.0 ± 4.2	116.9 ± 3.8	114.6 ± 3.6	99.9 ± 2.3	13.4 ± 11.0*
15	Elite	73	107.4 ± 2.3	108.1 ± 2.7	106.2 ± 2.1	100.7 ± 1.9	23.0 ± 16.9
15	High-competitive	511	114.8 ± 3.7	115.6 ± 3.6	113.1 ± 3.2	100.7 ± 2.0	15.6 ± 11.3*
16	Elite	104	106.9 ± 2.1	107.9 ± 2.3	106.2 ± 1.8	100.9 ± 1.7	20.4 ± 15.1
16	High-competitive	549	113.4 ± 3.0	114.3 ± 3.1	112.1 ± 2.7	100.8 ± 1.9	14.7 ± 11.4*
17	Elite	120	106.5 ± 2.0	107.4 ± 2.0	105.9 ± 1.8	100.9 ± 1.3	20.0 ± 15.9
17	High-competitive	493	112.8 ± 3.0	114.0 ± 3.1	111.8 ± 2.8	101.1 ± 1.9	14.9 ± 11.4*
18	Elite	110	105.9 ± 1.7	106.6 ± 1.7	105.3 ± 1.7	100.7 ± 1.4	20.7 ± 17.9
18	High-competitive	297	111.0 ± 2.4	112.0 ± 2.4	110.1 ± 2.0	101.0 ± 1.7	15.3 ± 11.5*
19	Elite	121	105.6 ± 1.7	106.6 ± 2.2	105.1 ± 1.9	100.9 ± 1.4	22.1 ± 17.5
19	High-competitive	244	110.6 ± 2.3	111.7 ± 2.4	109.7 ± 1.9	101.0 ± 1.7	16.3 ± 11.6*
20	Elite	116	105.4 ± 1.9	106.3 ± 2.0	104.7 ± 1.7	100.9 ± 1.2	26.0 ± 21.5
20	High-competitive	193	110.5 ± 2.3	111.7 ± 2.6	109.4 ± 2.0	101.2 ± 1.6	18.6 ± 10.9*
21	Elite	107	105.0 ± 1.8	106.0 ± 2.0	104.4 ± 1.7	100.9 ± 1.5	27.1 ± 21.5
21	High-competitive	67	109.0 ± 1.6	110.0 ± 1.7	108.1 ± 1.1	100.9 ± 1.4	17.9 ± 11.5*
22	Elite	87	104.9 ± 1.7	105.8 ± 1.9	104.4 ± 1.6	100.9 ± 1.3	24.4 ± 18.2
22	High-competitive	47	109.2 ± 1.4	109.9 ± 1.8	108.0 ± 1.0	100.6 ± 1.5	17.5 ± 11.2*

Note. *indicates significant difference (tested for PPa and PPb) between elite performance group, $p < 0.05$

Appendix D. Test statistics of independent sample t-tests and Mann Whitney tests for talented male swimmers.

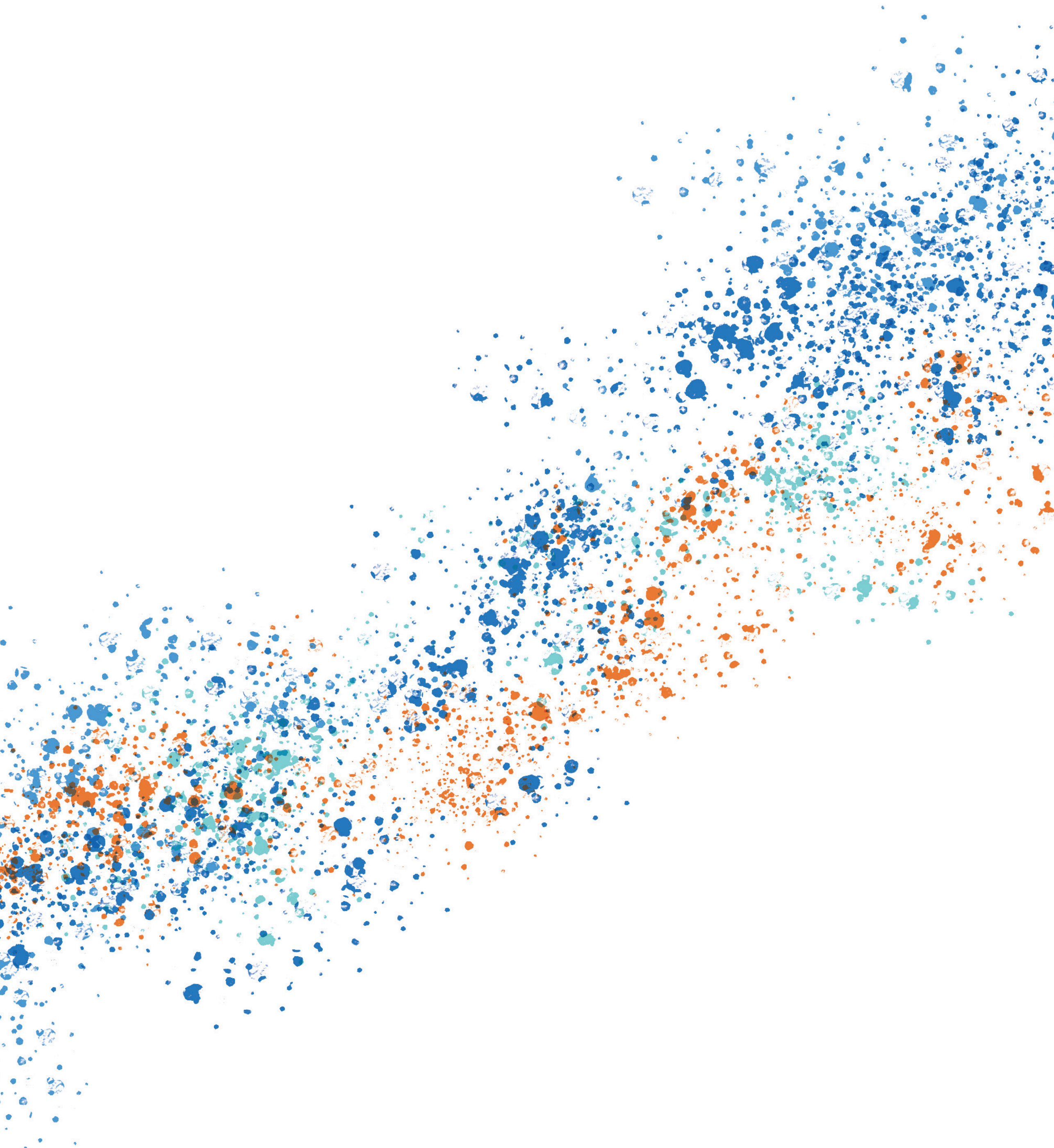
			PP_A		
Age	t or U	*Df*	p	CI	r or *d*
14*	217.00		0.037		0.18
15*	1,537.00		0.582		0.03
16*	4,698.00		0.215		0.06
17	-1.536	488	0.125	[-1.1 - 0.15]	-0.26
18	-1.775	492	0.076	[-0.99 - 0.05]	-0.24
19	-1.040	536	0.299	[-0.62 - 0.19]	-0.12
20	0.445	366	0.657	[-0.30 -0.47]	0.05
21	-0.824	364	0.410	[-0.57 - 0.23]	-0.10
22	0.212	214	0.832	[-0.40 - 0.43]	0.03
23	1.248	154	0.214	[-0.18 - 0.81]	0.14
24	-0.889	91	0.376	[-0.79 - 0.30]	-0.14
			PP_B		
Age	t or U	*Df*	p	CI	r or *d*
14*	124.00		0.113		0.14
15*	978.00		0.010		0.15
16*	2,401.00		0.001		0.16
17	3.433	40.249	0.001	[4.0 - 15.6]	0.77
18	2.180	68.567	0.033	[0.45 -10.1]	0.39
19	4.345	98.815	<0.001	[5.3 - 14.1]	0.70
20	3.283	117.111	0.001	[3.4 - 13.8]	0.49
21	4.064	120.361	<0.001	[5.1 - 14.9]	0.59
22	3.685	108.826	<0.001	[5.0 - 16.5]	0.59
23	2.805	85.717	0.006	[2.8 - 6.3]	0.03
24	2.058	60.276	0.044	[0.23 -15.7]	0.03

Note. *For age 14 through 16, Mann Whitney tests were performed instead of independent sample t-tests (test statistic is reported U and effect size is r)

Appendix E. Test statistics of independent sample t-tests and Mann Whitney tests for talented female swimmers.

			PP_A		
Age	t or U	*Df*	p	CI	r or *d*
12*	455		0.706		0.03
13*	2.420		0.665		0.03
14	0.989	417.000	0.323	[-0.42 - 1.30]	0.19
15	-2.390	582.000	0.811	[-0.56 - 0.44]	-0.03
16	0.431	651.000	0.667	[0.30 - 0.47]	0.05
17	-1.052	611.000	0.293	[-0.58 - 0.17]	-0.11
18	-1.487	405.000	0.138	[-0.64 - 0.09]	-0.17
19	-4.010	363.000	0.688	[-0.42 - 0.28]	-0.04
20	-1.612	307.000	0.108	[-0.63 - 0.06]	-0.19
21	0.081	172.000	0.935	[-0.43 - 0.47]	0.01
22	1.380	132.000	0.170	[-0.15 - 0.84]	0.25
			PP_B		
Age	t or U	*Df*	p	CI	r or *d*
12*	318.00		0.110		0.13
13*	1,743.00		0.013		0.15
14	3.712	31.633	0.001	[4.5 - 15.5]	0.89
15	3.632	81.476	<0.001	[3.4 - 11.5]	0.61
16	3.677	126.220	<0.001	[2.6 - 8.8]	0.47
17	3.318	150.036	0.001	[2.1 - 8.1]	0.41
18	2.950	143.183	0.004	[1.8 - 9.0]	0.40
19	3.281	172.146	0.001	[2.3 - 9.3]	0.42
20	3.427	151.112	0.001	[3.1 - 11.6]	0.47
21	3.662	168.445	<0.001	[4.2 - 14.1]	0.50
22	2.703	129.481	0.008	[1.8 - 11.9]	0.43

Note. *For age 12 through 13, Mann Whitney tests were performed instead of independent sample t-tests (test statistic is U and effect size is r)



Chapter 4

Pacing behavior development in adolescent swimmers: A large-scale longitudinal data analysis

Menting, S. G. P*., Post, A. K*., Nijenhuis, S. B., Koning, R. H., Visscher, C., Hettinga, F. J., & Elferink-Gemser, M. T. (2023). Pacing behavior development in adolescent swimmers: A large-scale longitudinal data analysis. *Medicine and Science in Sports and Exercise, 55*(4), 700-709. https://doi.org/10.1249/MSS.0000000000003086

*These authors contributed equally to this work.

Abstract

Purpose

Use a large-scale longitudinal design to investigate the development of the distribution of effort (e.g., pacing) in adolescent swimmers, specifically disentangling the effects of age and experience and differentiating between performance levels in adulthood.

Methods

Season best times and 50m split times of 100m and 200m freestyle swimmers from five continents were gathered between 2000 and 2021. Included swimmers competed in a minimum of three seasons between 12-24 years old (5.3±1.9 seasons) and were categorized by performance level in adulthood (elite, sub-elite, high-competitive) (100m: n=3498, 47% female; 200m: n=2230, 56% female). Multilevel models in which repeated measures (level 1) were nested within individual swimmers (level 2) were estimated to test the effects of age, race experience, and adult performance level on the percentage of total race time spent in each 50m section (p <0.05).

Results

In the 100m, male swimmers develop a relatively faster first 50m when becoming older. This behavior also distinguishes elite from high-competitive swimmers. No such effects were found for female swimmers. Conversely, more experienced male and female swimmers exhibit a slower initial 50m. With age and race experience, swimmers develop a more even velocity distribution in the 200m. Adolescent swimmers reaching the elite level adopt a more even behavior compared to high-competitive. This differentiation occurs at younger age in female (>13 years) compared to male (>16 years) swimmers.

Conclusion

Pacing behavior development throughout adolescence is driven by age-related factors besides race experience. Swimmers attaining a higher performance level during adulthood exhibit a pacing behavior which better fits the task demands during adolescence. Monitoring and individually optimizing the pacing behavior of young swimmers is an important step towards elite performance.

Keywords

Sport, race analysis, competitive swimming, future performance, talent, multilevel modelling.

Introduction

The goal-directed decision-making process regarding effort distribution (i.e., pacing) is a decisive factor for performance in exercise tasks (Edwards & Polman, 2012; Smits et al., 2014). The outcome of this process, the athletes' pacing behavior, is commonly quantified by registering a measure of effort (e.g., power output or velocity) during sections of an exercise task (Smits et al., 2014; Foster et al., 2003). Pacing seems to be learned through a cyclical acquisition process, in which experience gathered during a previous task is used to inform the athlete in future iterations of the task (Elferink-Gemser & Hettinga, 2017). The awareness of the benefits of distributing effort to reach a set exercise goal is first observed at 5-8 years old (Micklewright et al., 2012) and the capability to do this effectively continues to develop during adolescence and into adulthood (Wiersma et al., 2017; Menting et al., 2020). With age, the pacing behavior of children and adolescents develops to feature an increasing fit to the task demands (Wiersma et al., 2017; Menting et al., 2020). Previous longitudinal studies considered the pacing behavior exhibited by elite level adults as the endpoint of this development (Wiersma et al., 2017; Menting et al., 2020). Moreover, it was revealed that athletes who reached a higher performance level in adulthood, exhibited a pacing behavior resembling that of adult athletes at an earlier stage of adolescence, compared to their less successful peers (Wiersma et al., 2017). Knowledge about the development of pacing behavior is therefore of great interest for both scientists and practitioners. Unfortunately, the limited amount of available research into the pacing behavior of children and adolescents consists mainly of cross-sectional studies with small sample sizes, often including individuals from one specific country, region, school, club or team (Menting et al., 2019a; Menting et al, 2019b). To provide further insights into the development of pacing behavior, more rigorous longitudinal studies with large sample sizes are needed.

One sport in which the topic of pacing behavior has gained increasing scientific interest in the last few years, is competitive swimming (Menting et al., 2019a; McGibbon et al., 2018). Given the highly resistive properties of water compared to air, and the low mechanical efficiency of the swimming movement, it has been argued that adequate pacing might be more important in swimming compared to land-based sports (Menting et al., 2019a; McGibbon et al., 2018). Moreover, competitive swimming is a popular, global sport in which the gap between the gold medalist and the last finisher in international competitions is decreasing (FINA, 2021). In light of this, optimizing pacing behavior plays an increasingly important role in elite swimming performance (Menting et al., 2019a; McGibbon et al., 2018). Systematic literature reviews have shown that pacing behavior of swimmers is primarily determined by the race distance and stroke type (Menting et al., 2019a; McGibbon et al., 2018). In races over a short distance (50-100m), elite swimmers adopt an all-out pacing behavior, attempting to achieve a high velocity through rapid acceleration and trying to maintain this velocity throughout the race (Robertson et al, 2009). During 200m races, elite swimmers adopt a fast start followed by an even pace (Skorski et al., 2014a). Comparing different strokes, it is evident that the butterfly and breaststroke events are characterized by a gradual decrease in velocity over the duration of the race, which is mostly attributed to the relative inefficiency of these strokes compared to front crawl or backstroke. Regarding pacing behavior development in swimming, one study reported that adolescent swimmers performing a 200m front crawl trial started off too fast and therefore lacked in speed at the end of the trial (Scruton et al., 2015). A second study reported that adolescent swimmers have difficulty in selecting the optimal pace, performing better in a 400m front crawl trial when executing an externally imposed pace compared to a self-selected pace (Skorski et al., 2014b). It was proposed that the difference between adolescent and adult swimmers was due to the disparity in task experience (Skorski et al., 2019a; Turner et al., 2008; Dormehl & Osborough, 2015). This, however, seems to be an oversimplification as the shift of pacing behavior during adolescence is thought to originate not only from increased exercise experience but also from age-related physical maturation and cognitive development (Elferink-Gemser & Hettinga 2017; Menting et al., 2019b). Additionally, as the chronology of physical maturation and cognitive development processes differ between boys and girls (Buckler & Wild, 1987; Arain et al., 2013), it logically follows that the timeline of pacing behavior development differs between sexes (Menting et al., 2019c; Menting et al., 2022). A profound understanding of the mechanisms behind the pacing behavior of adolescent swimmers, including the influence of factors such as age, experience and sex, could help coaches to guide their athletes in developing a more optimal pacing behavior.

The present study aimed to investigate the development of pacing behavior in adolescent swimmers, specifically disentangling the effects of age and experience and differentiating between performance levels in adulthood. It was hypothesized that the pacing behavior of swimmers would develop during adolescence, gradually exhibiting more resemblance to adult behavior. The demands of the task would influence the direction of the development. In short tasks, the development would present itself as a change towards a more all-out pacing behavior, characterized by a higher velocity during the initial stages. In longer tasks, the shift would be towards a more even effort distribution. Moreover, it was hypothesized that, independent of age, increased experience would facilitate a better fit with the task demands: a higher velocity in the initial stages in the shorter tasks and an overall more even distribution of effort in longer tasks. Adolescent swimmers who eventually reached a higher performance level in adulthood were hypothesized to exhibit a pacing behavior more resembling that of adult swimmers, compared to adolescent swimmers who attained a lower performance level. As females generally exhibit puberty-related physical maturation and cognitive development at an earlier age compared to their male counterparts, it was hypothesized that the split between swimmers of different future performance levels would occur earlier in females compared to males.

Methods

All procedures used in the study were approved by the Local Ethical Committee of the University Medical Center Groningen, University of Groningen, The Netherlands (201900334) in the spirit of the Helsinki Declaration. The requirement for informed consent of the participants was waived given the fact that the study involved the analysis of publicly available data and analyses were group-based.

Data collection

All available 100m and 200m freestyle long course performance data (i.e., date of the race, total race time and available 50m split times) of both male and female swimmers performing between 2000 and 2021, were collected from Swimrankings' database (Swimrankings, 2021). This resulted in 2,857,181 (100m freestyle) and 1,897,872 (200m freestyle) observations. The assumption was made that all swimmers chose the front crawl during the freestyle events. Performance data were collected from 113 countries across the world. The date of birth of all included swimmers was collected using the same database.

Data processing

Swim performances over 180s (100m freestyle) and 360s (200m freestyle) were excluded from the analysis to ensure a homogeneous dataset. Performance data were classified per swimming season, starting on the 1st of September and ending on the 31st of August of the next calendar year. Data from the 1st of January 2008-2010 were excluded from analysis, because of the impact of full-body polyurethane swimsuits on swimming performance in that period (Tiozzo et al., 2009; Toussaint et al., 2002; Tomikawa & Nomura., 2009). Performance data from season 2019-2020 were excluded as competitions and training opportunities were disturbed because of the COVID-19 pandemic. A total of 2,773,387 observations (100m freestyle) and 1,842,992 (200m freestyle) observations remained. For each swimmer, the Season Best Time (SBT) per swimming season was used for further analysis. Age at SBT was determined using the swimmer's date of birth. Race experience was defined as the cumulative number of races of a specific event, which the swimmers had completed before SBT.

Inclusion criteria

For the purpose of this study, it was important to outline the development of pacing behavior from a young age on toward the age of peak performance. Peak performance in competitive swimming is on reached at 24 (±2) years for males and at 22 (±2) years for females (Allen et al., 2015). Therefore, only swimmers who had at least one swim performance in the age category of 22 years or older (male) or 20 years or older (female) were included. To ensure a dataset representing the developmental pathway of pacing behavior towards peak performance, swim performances after the swimmer's career-best swim performance were excluded. To longitudinally study pacing behavior development, included swimmers had to be between 12 and 24 years old and have performance data with 50m split times in at least three swimming seasons. To study pacing behavior independent of current performance, split times of each 50m section were converted into relative section times (RST), representing the percentage of the total race time spent in one section. The inclusion criteria were conducted for the 100m and 200m events separately.

Swim performances of multiple generations (i.e., from 2000 through 2021) were included in the dataset, which necessitated the correction of evolution in competitive swimming. As such, swim performances were defined as a percentage of the prevailing world record (WR) of the corresponding sex, referred to as relative Season Best Time (rSBT) (Post et al., 2020; Stoter et al., 2019). World records from 2008 and 2009 were replaced by the prevailing fastest time in a textile swimsuit. According to the event, swimmers were allocated to the elite, sub-elite or high-competitive performance group by using their event-specific all-time rSBT after 20 (female) or 22 (male) years of age (see **Table 1**). The elite level was defined as the average rSBT of the 50th swimmer of the event-specific FINA World Ranking List between 2016 and 2021 (FINA, 2021). Sub-elite level and high-competitive level were defined as the average rSBT of the 8th and 50th swimmer of the event-specific National Ranking List of the Netherlands between 2016 and 2021 (FINA, 2021). Swimmers with a best rSBT outside the limits of the high-competitive group were excluded from further analysis. For the 100m event, this resulted in 3,498 swimmers (1,659 female) with 15,960 observations (7,384 female) with an average of 5.3 ± 1.9 observations per swimmer. For the 200m event, this resulted in 2,230 swimmers (1,252 female) with 10,309 observations (5,412 female) with an average of 5.3 ± 1.9 observations per swimmer.

Table 1. Total number of swimmers and observations according to sex, performance level and event included in the analysis.

	Performance level limits	Individuals	Observations
Male (100m freestyle)			
Elite	best rSBT ≤ 103.7%	145	756
Sub-elite	103.7% < best rSBT ≤ 107.4%	501	2,472
High-competitive	107.4% < best rSBT ≤ 114.7%	1,193	5,348
Total		1,839	8,576
Male (200m freestyle)			
Elite	best rSBT ≤ 104.1%	104	524
Sub-elite	104.1% < best rSBT ≤ 107.6%	314	1,548
High-competitive	107.6% < best rSBT ≤ 116.6%	650	2,825
Total		1,068	4,897
Female (100m freestyle)			
Elite	best rSBT ≤ 105.2%	175	940
Sub-elite	105.2% < best rSBT ≤ 107.5%	265	1,289
High-competitive	107.5% < best rSBT ≤ 115.0%	1,219	5,155
Total		1,659	7,384
Female (200m freestyle)			
Elite	best rSBT ≤ 104.2%	142	704
Sub-elite	104.2% < best rSBT ≤ 107.5%	315	1,455
High-competitive	107.5% < best rSBT ≤ 115.8%	795	3,253
Total		1,252	5,412

Statistical analysis

Following the methods introduced by Menting et al. (2020), longitudinal multilevel models were created to describe pacing behavior as a function of age, race experience and performance group. Multilevel modelling allows for the creation of models in which repeated measures (level 1) are nested within individual swimmers (level 2), allowing the use of longitudinal data with varying number of measurements between swimmers as well as a variety in temporal spacing between measurements. Analyses were performed using the lmer4 package in R (R version 3.6.0) (R Core Team, 2019; Bates et al., (2015). Statistical assumptions (e.g., multicollinearity) were checked and outliers were screened and removed (100m: 915, 200m: 1,006). The RST per 50m section were included as dependent variables. In contrast to split times, all RST must add up to 100%. With respect to this constraint, one out of two (100m freestyle) and three out of four (200m freestyle) multilevel models were created. The remaining, free section (RST 50-100m in both events) was calculated from these models. Following that the sum of 50m sections must add up to 100%, the same predictor variables (fixed part) and variance structure (random part) had to be incorporated into each model equation.

Predictor variables age and race experience were included as continuous, time-varying factors whereas performance group was included as a categorical, time-invariant factor. The power law of practice states that the effect of experience on performance decreases as the level of experience increases (Schmidt et al., 2018). In addition, the age effect on performance decreases as swimmers are fully matured (Post et al., 20). As such, the effect of a 1-year increase at age 13 will be larger than a 1-year increase at age 19. To account for this, the variables age and race experience were log-transformed, of which the latter transformation was needed to meet the assumption of normality. To represent the three performance groups in the statistical models, two dummy variables (sub-elite and high-competitive) were included and the elite group functioned as reference level. A random intercept model was selected as the most appropriate variance structure, allowing the inclusion of each swimmer's individual trajectory that randomly deviates from the average population trajectory. In sum, the following multilevel model was adopted:

$$RST_{is} = \alpha_i + \beta_1 \times \log(Age_{is}) + \beta_2 \times \log(RaceExperience_{is}) + \beta_3 \times SubElite_i + \beta_4 \times HighCompetitive_i + u_i + \varepsilon_{is}$$

$$u_i \sim N(0, \sigma_0^2)$$

$$\varepsilon_{is} \sim N(0, \sigma^2)$$

RST_{is} was the relative split time of a 50m section for swimming season s of swimmer i,α_i the intercept assigned to the elite group, Age_{is} the corresponding age value, $RaceExperience_{is}$, the corresponding race experience value, $SubElite_i$ the dummy variable of swimmer i assigned to the sub-elite group and $HighCompetitive_i$ the dummy variable of swimmer i assigned to the high-competitive group. The unexplained information was the sum of u_i (between-subject variance) and (residual variance). The models were validated by using graphical tools to check violations of homogeneity, normality and independence. Predictor variables were considered significant if the estimated coefficient is greater than twice the standard error of the estimate (p <0.05).

Post-hoc analyses were performed for models with future performance group as significant predictor variable. For this analysis, swimmers were classified in age categories based on their age on the 31st of December of the swimming season. Per age category, an independent sample t-test was conducted to examine from which age onward between-group differences in pacing behavior occurred. These follow-up analyses were executed for age categories with at least 30 observations per performance group. For all tests, p < 0.05 (two-tailed) was set as significance.

Results

The models created can be found in **Table 2**. Using the fixed part of the models, predictions for the dependent variables can be made. For example, for the RST in the 100-150m segment of a 200m event performed by an 18-year-old male swimmer, with 20 previous races and an adult performance level as high-competitive, the following value will be predicted as:

$$\begin{aligned} RST\ 150m &= 27.42 + (-0.55 \times \log 18) + (-0.03 \times \log 20) + (-0.00 \times 0) + (0.09 \times 1) \\ &= 25.83\% \end{aligned}$$

Age

The predicted effect of age on RST is visualized in **Figure 1A** (100m) and **Figure 2A** (200m). Older male swimmers were relatively faster in the first 50m of the 100m. No effect of age was indicated in female 100m swimmers. In the 200m, older male and female swimmers were predicted to start relatively slower, have a relatively faster middle section and a relatively slower final 50m section compared with their younger counterparts.

Race experience

Race experience significantly impacted RST in all segments except for the final segment in the male 200m event, as visualized in **Figure 1B** (100m) and **Figure 2B** (200m). In the 100m, more experienced male and female swimmers were relatively slower in the first half of the race. In the 200m, male swimmers with more race experience were relatively slower in the first 50m section, but faster in the 150m section. More experienced female swimmers were relatively slower in the first 50m section and relatively faster in the 150m and 200m sections.

Performance level

Elite male swimmers were faster in the first 50m of the 100m, compared to the high-competitive group. Post hoc analysis revealed that the male swimmers of the elite group started differentiating themselves at 17 years old ($t_{(99.6)} = -2.21$, $p < 0.05$). No difference was found between female swimmers of differing performance groups. In the 200m, elite male swimmers were predicted to be relatively slower in the first 50m, but faster in the 150m section, compared to swimmers from the high-competitive group. Swimmers from the elite group differentiated themselves as early as 16 years old (RST50: $t_{(51.728)} = 3.10$, $p < 0.01$; RST150: $t_{(57.699)} = 3.11$, $p < 0.01$). Elite female swimmers were relatively slower in the first 50m section, but faster in the 150m and 200m sections, compared to the high-competitive group. The difference started at 13 years of age (RST50: $t_{(51.07)} = 2.36$, $p < 0.05$, RST150: $t_{(77,62)} = 4.62$, $p < 0.001$; RST200: $t_{(97,66)} = -3.065$, $p < 0.01$). In both the 100m and 200m, the model predicted no significant difference in RST between the elite and sub-elite groups (**Figure 1C and Figure 2C**).

Table 2. Multilevel models predicting relative section time per 50m section, divided by sex and event.

	50-m				**100-m**			
	Estimates	*SE*	*CI*	*P*	*Estimates*	*SE*	*CI*	*P*
Male (100m Freestyle)								
Fixed Effects								
Intercept	48.90	0.15	48.61 – 49.19	<0.001	51.10	-	-	-
Age[a]	-0.30	0.05	-0.40 – -0.20	**<0.001**	0.30	-	-	-
Race experience[a]	0.02	0.01	0.01 – 0.04	**0.006**	-0.02	-	-	-
Elite vs Sub-elite	0.05	0.04	-0.02 – 0.12	0.190	-0.05	-	-	-
Elite vs High-competitive	0.12	0.03	0.06 – 0.19	**<0.001**	-0.12	-	-	-
Random Effects								
σ2	0.22							
T_{00}	0.11							
ICC	0.33							
Marginal R^2 / Conditional R^2	0.011 / 0.334							

	50-m				**100-m**				**150-m**				**200-m**			
	Estimates	*SE*	*CI*	*P*	*Estimates*	*SE*	*CI*	*P*	*Estimates*	*SE*	*CI*	*P*	*Estimates*	*SE*	*CI*	*P*
Male (200m Freestyle)																
Fixed Effects																
Intercept	22.20	0.14	21.94 – 22.47	<0.001	26.14	-	-	-	27.42	0.10	27.23 – 27.61	<0.001	24.24	0.16	23.92 – 24.55	<0.001
Age[a]	0.38	0.05	0.28 – 0.47	**<0.001**	-0.26	-	-	-	-0.55	0.03	-0.62 – -0.48	**<0.001**	0.43	0.06	0.32 – 0.54	<0.001
Race experience[a]	0.05	0.01	0.03 – 0.06	**<0.001**	-0.01	-	-	-	-0.03	0.01	-0.04 – -0.02	**<0.001**	-0.01	0.01	-0.03 – 0.01	0.240
Elite vs Sub-elite	0.03	0.03	-0.03 – 0.09	0.412	-0.00	-	-	-	-0.00	0.02	-0.04 – 0.04	0.858	-0.02	0.03	-0.09 – 0.04	0.495
Elite vs High-competitive	-0.11	0.03	-0.16 – -0.05	**<0.001**	-0.03	-	-	-	0.09	0.02	0.06 – 0.13	**<0.001**	0.04	0.03	-0.02 – 0.10	0.150
Random Effects																
σ2	0.10								0.06				0.17			
T_{00}	0.05								0.02				0.05			
ICC	0.34								0.23				0.22			
Marginal R^2 / Conditional R^2	0.086 / 0.395								0.152 / 0.345				0.020 / 0.233			

	50-m				100-m			
	Estimates	*SE*	*CI*	*P*	*Estimates*	*SE*	*CI*	*P*
Female (100m Freestyle)								
Fixed Effects								
Intercept	48.06	0.13	47.80 – 48.31	<0.001	51.94	-	-	-
Age[a]	0.06	0.05	-0.03 – 0.15	0.215	-0.06	-	-	-
Race experience[a]	0.04	0.01	0.02 – 0.05	**<0.001**	-0.04	-	-	-
Elite vs Sub-elite	-0.03	0.03	-0.10 – 0.03	0.331	0.03	-	-	-
Elite vs High-competitive	-0.05	0.03	-0.10 – 0.01	0.095	0.05	-	-	-
Random Effects								
σ2	0.17							
T_{00}	0.08							
ICC	0.33							
Marginal R^2 / Conditional R^2	0.010 / 0.335							

	50-m				100-m				150-m				200-m			
	Estimates	*SE*	*CI*	*P*	*Estimates*	*SE*	*CI*	*P*	*Estimates*	*SE*	*CI*	*P*	*Estimates*	*SE*	*CI*	*P*
Female (200m Freestyle)																
Fixed Effects																
Intercept	22.24	0.12	22.01 – 22.46	<0.001	26.02	-	-	-	27.15	0.08	26.99 – 27.31	<0.001	24.60	0.12	24.36 – 24.84	<0.001
Age[a]	0.40	0.04	0.32 – 0.49	**<0.001**	-0.24	-	-	-	-0.47	0.03	-0.52 – -0.41	**<0.001**	0.30	0.05	0.22 – 0.39	**<0.001**
Race experience[a]	0.06	0.01	0.05 – 0.07	**<0.001**	-0.00	-	-	-	-0.04	0.00	-0.04 – -0.03	**<0.001**	-0.02	0.01	-0.04 – -0.01	**<0.001**
Elite vs Sub-elite	-0.01	0.03	-0.07 – 0.04	0.616	-0.02	-	-	-	0.01	0.02	-0.03 – 0.04	0.719	0.03	0.03	-0.02 – 0.08	0.203
Elite vs High-competitive	-0.18	0.02	-0.23 – -0.14	**<0.001**	0.00	-	-	-	0.11	0.02	0.08 – 0.14	**<0.001**	0.07	0.02	0.03 – 0.12	**0.001**
Random Effects																
σ2	0.09				-				0.05				0.12			
T_{00}	0.05				-				0.02				0.03			
ICC	0.37				-				0.26				0.21			
Marginal R^2 / Conditional R^2	0.142 / 0.463				-				0.166 / 0.380				0.015 / 0.225			

Note. [a]The variables age and race experience were log-transformed. The P value of significant predictor variables (α-<-0.05) indicated in bold.

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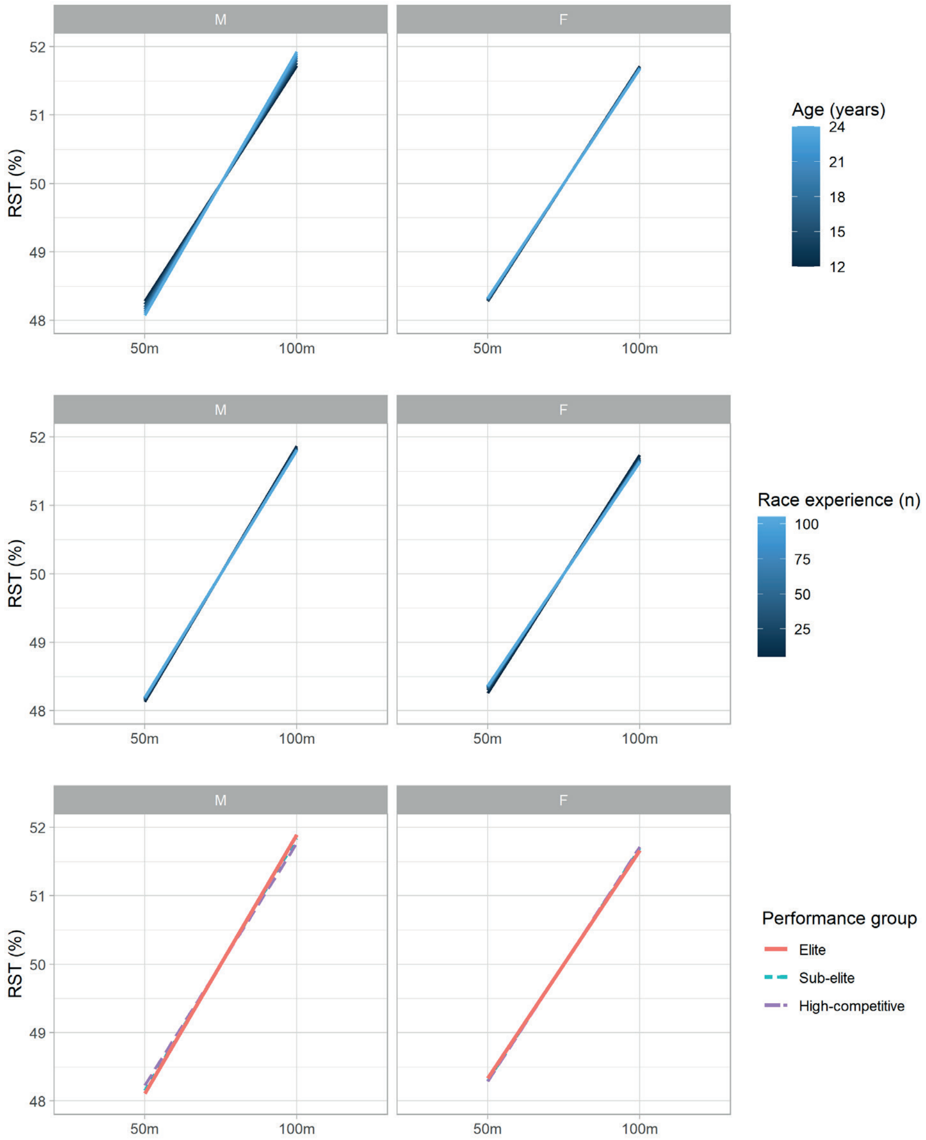

Figure 1. Predicted pacing behavior for males and females in the 100m freestyle event according to age, race experience and performance level.

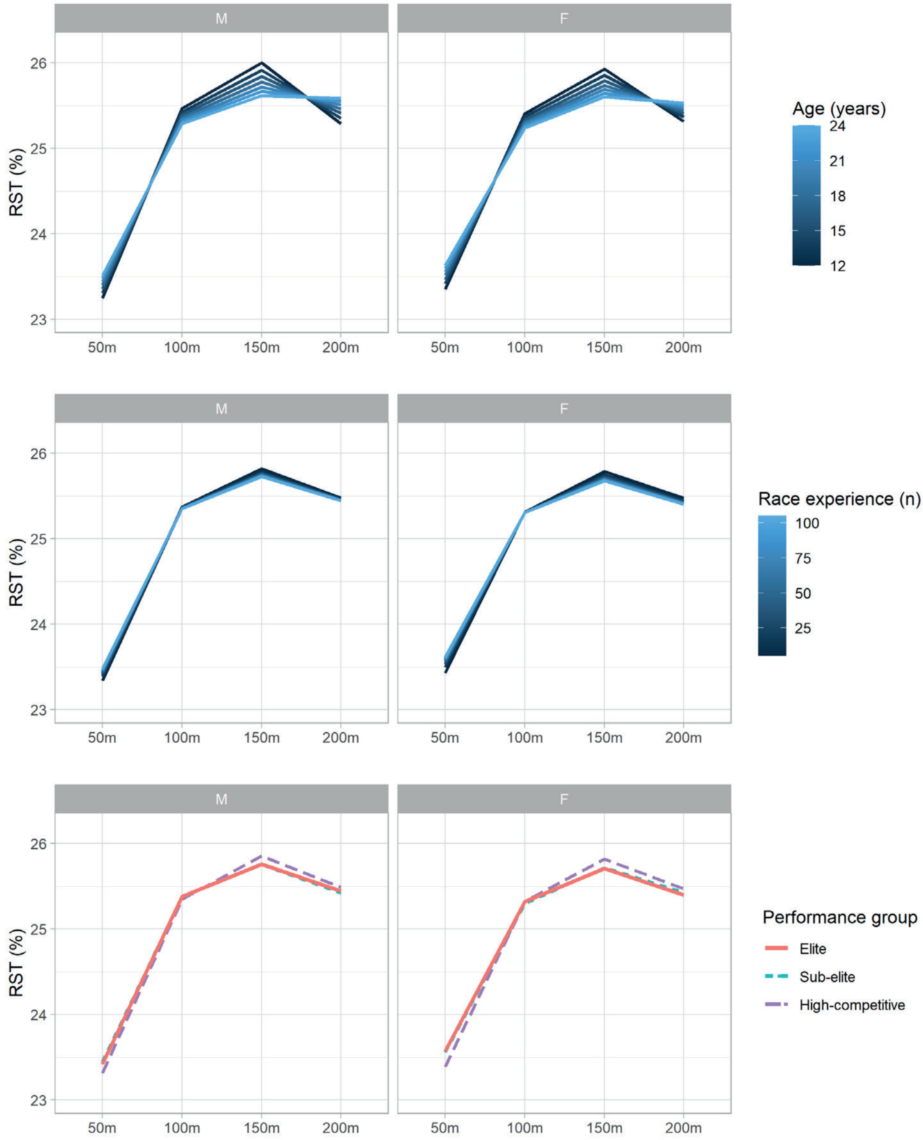

Figure 2. Predicted pacing behavior for males and females in the 200m freestyle event according to age, race experience and performance level.

Discussion

The present study aimed to investigate the pacing behavior development of swimmers throughout adolescence, explicitly differentiating between the effects of age and experience as well as investigating its relationship to performance level in adulthood. As hypothesized, older male swimmers adopted a more all-out distribution of effort in the 100m event, although this development was not exhibited by female swimmers. In the 200m, male and female swimmers exhibited a more even distribution of effort as they became older. Both race experience and age independently impacted the pacing behavior of adolescent swimmers, providing evidence that experience is not the sole driver of pacing behavior development. Furthermore, adolescent swimmers who in adulthood reached the elite level (100m: male, 200m: male & female) exhibited a pacing behavior more resembling adult swimmers compared to swimmers in the high-competitive group. As hypothesized, the distinction in pacing behavior between swimmers of differing future performance level occurred earlier in female compared to male swimmers.

Pacing behavior development in swimming

In previous literature, the effect of experience and age has often been used synonymously (Skorski et al., 2014a; Turner et al., 2008; Dormehl & Osborough, 2015). However, this seems to be an oversimplification. In the 100m, the behavior of older male swimmers moves towards a fast first 50m, hereby paralleling the behavior of the elite swimmers in adulthood. This resemblance, however, was not observed when comparing male swimmers based on race experience. It supports the notion that pacing behavior development is driven by other age-related factors (e.g., physical maturation and cognitive development) alongside the increase in experience. Additionally, these findings suggest that race experience in itself may not be sufficient to explain the development of future elite performers. Further evidence for this view is provided by the finding that in the 200m event, age still impacts on pacing behavior in both male and female swimmers, even with a separate variable for race experience included in the model. Moreover, the results show that in line with the hypothesis, the separation between future performance levels occurs at a younger age in females (13 years old) compared to males (16 years old). The earlier onset of pacing behavior development in females which has previously been described in a cross-sectional study (Menting et al., 2019c) is thereby confirmed by the current longitudinal study and is thought to be caused by the earlier onset of physical maturation and cognitive development (Menting et al., 2019c; Menting et al., 2022).

Based on previous literature, it was proposed that with experience and age, adolescent athletes adapt their pacing behavior to better fit the task demands (Wiersma et al., 2017; Menting et al., 2020). Indeed, within the present study, there is a difference in the development of pacing behavior in the 100m and the 200m events. In the 100m event, older male swimmers adopt a more all-out pacing behavior, characterized by a relatively faster first lap. The relatively faster initial 50m could be the result of an improved race start, including the dive and underwater phase. Alternatively, it has been established that in tasks of similar duration to the 100m freestyle event, better-performing athletes differentiated themselves by a relatively more all-out pacing behavior (Hanon & Gajer, 2009; De Koning et al., 1999). De Koning et al. (1999) proposed that for shorter events (<2min), the advantage of a higher velocity in the first part of an exercise task and the lower amount of kinetic energy left at the end of the race, outweighed the disadvantage of higher frictional losses associated with the higher average velocity (De Koning et al., 1999), which was further evidenced through modelling studies in speed skating and track cycling (Hettinga et al., 2011; Hettinga et al., 2012), though differences between sports were visible (Stoter et al., 2016). Indeed, elite swimmers competing in the 100m freestyle finals of international events exhibited an all-out pacing behavior, comparable to the one found in the current study (Robertson et al., 2009). Moreover, it was reported that elite male swimmers adopted a more all-out pacing behavior (RST50m: 47.91%, RST100m: 52.09%) compared to female swimmers (RST 50m: 48.29%, RST100m: 51.77%) (Robertson et al., 2009). These findings are supported by the results of the present study, as adolescent male swimmers not only presented a more all-out pacing behavior, but also continued to develop this behavior with age. The reason behind the apparent difference in pacing behavior between male and female swimmers could potentially be found in the physical and physiological differences between male and female swimmers (Almeida et al., 2020). Alternatively, it has been reported that males engage more in risk-taking behavior and therefore are expected to generally adopt a more all-out pacing behavior (Micklewright et al., 2015).

Contrary to the 100m event, older male and female swimmers adopt a relatively more even distribution of velocity in the 200m event. This is achieved by a relatively slower first and last 50m section and a relatively faster middle section. Swimming is a head-to-head type event, as the winner of a race is the swimmer who covers the given distance before the other swimmers, independent of the time set by swimmers in previous races (Menting et al., 2019a). Remarkably, the development of pacing behavior in swimming does not resemble that of other middle-distance head-to-head events, such as short-track speed skating. Studies in these events have reported that the athletes' pacing behavior develops towards a more conservative start and middle section of the race to facilitate the athlete to position themselves well and be relatively faster in the key final stages of the race (Menting et al., 2020; Menting et al., 2019c; Menting et al., 2022). The development of pacing behavior in the 200m more resembles the one found in time-trials of a similar duration (Wiersma et al., 2017; Blasco-Lafarga et al., 2013; Sollie et al., 2021). This development is characterized by a shift towards a more even distribution of effort, which allows for a minimization of energy loss due to acceleration and deceleration, resulting in better performance in middle- and long-distance time-trial based events (De Koning et al., 2011). This resemblance to time-trials likely originates from the lane-based nature of competitive swimming (Menting et al., 2019a). The lanes inhibit the interaction with other competitors, resulting in a less interactive competitive environment as is also found in time-trial events. Taken together, coaches could expect to encounter sex- and age-related differences in pacing behavior in adolescent swimmers of the same level of race experience. Additionally, as adolescent athletes get older, they adapt their pacing behavior to fit the characteristics of the task, with male swimmers adopting a more all-out behavior on the 100m and both male and female swimmers adopting a more even distribution of effort in the 200m event.

Future performance

The findings of the present study provide evidence that the swimmers who perform within 104% of the prevailing world record as adults (i.e., the elite group), exhibit pacing behavior that differentiates them from other adolescent swimmers (i.e., the high-competitive group). It therefore establishes that adequate pacing behavior development is an essential part of the developmental pathway towards elite swimming performance. In the 200m event, the effect of future performance level parallels the effects of age and race experience in both males and females. In other words, swimmers that achieve a higher level of performance in adulthood, exhibited a pacing behavior resembling that of older and more experienced swimmers during adolescence. This is different for the 100m event. Adolescent male swimmers who reach the elite level as an adult, exhibit a pacing behavior that is more resembling the pacing behavior of the older swimmers (all-out pacing behavior) compared to that of their peers who reach the high-competitive level. However, the current findings suggest that more race experience results in a more conservative first 50m in the 100m instead of going more all-out. The underlying mechanism for this converse effect of race experience on pacing behavior in 100m event remains unclear and warrants further research. In females no effect of either performance level or age was found, however the effect of race experience was equal to males.

In the present study, no distinction could be made between elite and sub-elite swimmers. A possible reason for this could be the high performance level of all included swimmers in the present study. To place it into context, for a male 200m swimmer competing in 2022, the performance levels equal a time of <106.18s (elite), 106.18-109.75s (sub-elite) and 109.75-118.93 (high-competitive). The Olympic Qualifying Time for Tokyo 2021 was set at 107.02s (FINA, 2021). In comparison to the current study, a previous study did report a difference in pacing behavior between three performance levels (Wiersma et al., 2017). However, Wiersma et al. (2017) determined adult performance using the season best performance at 18-19 years of age, whereas the present study used a more appropriate measure to indicate adult performance level: all-time peak performance after 20 (female) or 22 (male) years of age expressed as a percentage of the prevailing world record. Recalculating the performance level of the athletes in the previous study, using these methods results in a much wider spectrum of performance (elite: 113.8%, sub-elite: 120.6%, non-elite: 129.7%), could explain why the previous study did find a difference in pacing behavior development between the performance levels.

Limitations and future directions

Although the models created in the present study provide novel insights into the relationship between age, experience and pacing behavior, the models do not account for all the variance in a swimmers' pacing behavior. Pacing is a complex, psychophysiological process and even when the task characteristics are set, it is influenced by a multitude of factors relating to the individual (i.e., physical maturity, cognitive development, muscle fiber type distribution) and environment (i.e., coaching culture, training opportunities) (Edwards & Polman, 2012; Menting et al., 2019b; Renfree & Casado, 2018; Mallet et al., 2021). The absence of these factors has potentially led to the lower explained variance of the models. For example, there was no effect for age or performance level on pacing behavior in female swimmers competing in the 100m event. In males, the effect of age and performance group was also more pronounced in the 200m event compared to the 100m event. It could be that 100m freestyle performance is predominantly driven by the development of physical characteristics, such as muscle fiber type distribution, whereas in the 200m event the distribution of effort is a larger determination factor in the outcome of the race. However, another reason might be that the 100m freestyle is often contested by both 50m and 200m specialists. The energetic system requirements between the 50m and 200m freestyle events differ significantly and therefore swimmers who compete in these events are adapted to physiologically very different tasks (Almeida et al., 2020), therefore exhibiting a different pacing behavior. The coming together of these two types of specialized swimmers might have impacted the results of the present study. It should be pointed out that previous studies have evidenced that swimming performance is impacted by velocity in free swimming sections, but also by turns and underwater phases (Simbaña Escobar et al., 2018). Quantification using 25m or even 5m and 10m sections has previously been demonstrated to reveal more detailed definitions of impact of these factors on a swimmers' performance (Dormehl & Osborough, 2015; Simbaña Escobar et al., 2018). However, these data have to be gathered using camera set-ups and specialized software, which drastically decreases practicality and would have reduced the sample size greatly. In the end, the present study aimed to create models which could provide insight into the relation between age, experience and future performance level, not precisely predict each individual swimmers' pacing behavior. The large sample size, consisting of swimmers from five continents, and the strong longitudinal nature of the data are of key importance to the rigidity of the present study's design, not in the first place because more large scale longitudinal studies on pacing behavior development are needed (Elferink-Gemser & Hettinga, 2017; Menting et al., 2022). Consequently, the decision was made to use publicly available 50m split times. The choice for this approach does allow for future studies, using more detailed quantifications of pacing behavior and the inclusion of more individual and environmental factors, to provide additional insights into the development of pacing behavior in the 100m and 200m freestyle events.

Practical application

The effect of age and race experience on pacing behavior as reported in the present study are relatively small compared to that of task defining characteristics such as race duration or stroke type (Menting et al., 2019a). However, in a 200m freestyle, an average 0.16% difference in velocity distribution per 50m section (the difference between a 12 and 18-year-old male swimmer as calculated using the models in the present study) constitutes 0.20s. In a sport where 0.01 of a second can be the difference between winning and losing, a 0.20s difference in velocity distribution in every 50m section can indeed have a very real impact on competition performance. Using the formula provided in the present study, coaches could determine whether their swimmers are on track of developing the pacing behavior necessary to achieve the elite performance level. One point of notice should be made to this approach: the road to elite performance is not always linear and pacing is only a part of the skillset necessary to reach the top (Elferink-Gemser et al., 2011). In addition, it has been established that to pace adequately, athletes need to match their personal performance capacities to the task demands. Seeing as there is variation in each swimmer's performance capacities, a slightly different pacing behavior could be optimal for each swimmer. It is therefore important to take the outcomes of the formula from the present study as a starting point and take an individualized approach to the development of each swimmer. Within this approach, coaches are advised to provide the swimmers with opportunities to experiment with variants of their established pacing behavior (Elferink-Gemser & Hettinga, 2017). Introducing variability would provide swimmers with the opportunity to discover a more optimal match between their personal performance capacities and the task demands (Shea & Kohl, 1990). Coaches could induce this variation by providing augmented feedback via tools such as a stopwatch, pacer clock, wearable metronome, underwater lights or smart goggles (McGibbon et al., 2020). Demonstrating this method, a recent study reported that a three week training program in which adolescent swimmers were provided with feedback on their own pacing behavior was effective in increasing 400m freestyle performance (Tijani et al., 2021). Subsequently, practice of the new variation of pacing behavior could be further increased by gradually taking away sources of feedback and adding environmental factors such as opponents, therefore training the swimmers to maintain their capability of decision-making regarding effort distribution in a more realistic competitive environment (Menting et al., 2019b; McGibbon et al., 2020).

Conclusion

The current large-scale study is the first in its kind in that it investigates the pacing behavior of swimmers from five continents over a period spanning the last twenty years. The rigorous multilevel modelling approach with corrections for prevailing world records revealed insights on developmental patterns based on thousands of swimmers with on average five competitive seasons in adolescence. The pacing behavior of swimmers develops during adolescence, as older swimmers adopt a pacing behavior that better suits the task demands (100m: more all-out [males only], 200m: more even). Although swimming is a head-to-head type of competition, the development of pacing behavior resembles that of time-trial events, most likely due to the lane-based nature of the sport. The persistence of the effect of age on pacing behavior when race experience was also included as predicting variable, supports the hypothesis that pacing behavior development during adolescence is driven by other factors in addition to increased experience, such as physical maturation and cognitive development. Swimmers who reach the elite performance level in adulthood, exhibit a pacing behavior better suits the task demands and that resembles that of adults (100m: more all-out [only males], 200m: more even) during adolescence. In the 200m, this differentiation occurs earlier in females compared to males, most likely due to the earlier onset of age-related physical maturation and cognitive development in females. Coaches are advised to take notice of the complex development of pacing behavior which occurs throughout adolescence. Furthermore, coaches could use the data presented in the present study as a starting point for an individualized approach to optimize the pacing behavior development in their swimmers and better guide them on the road towards elite performance.

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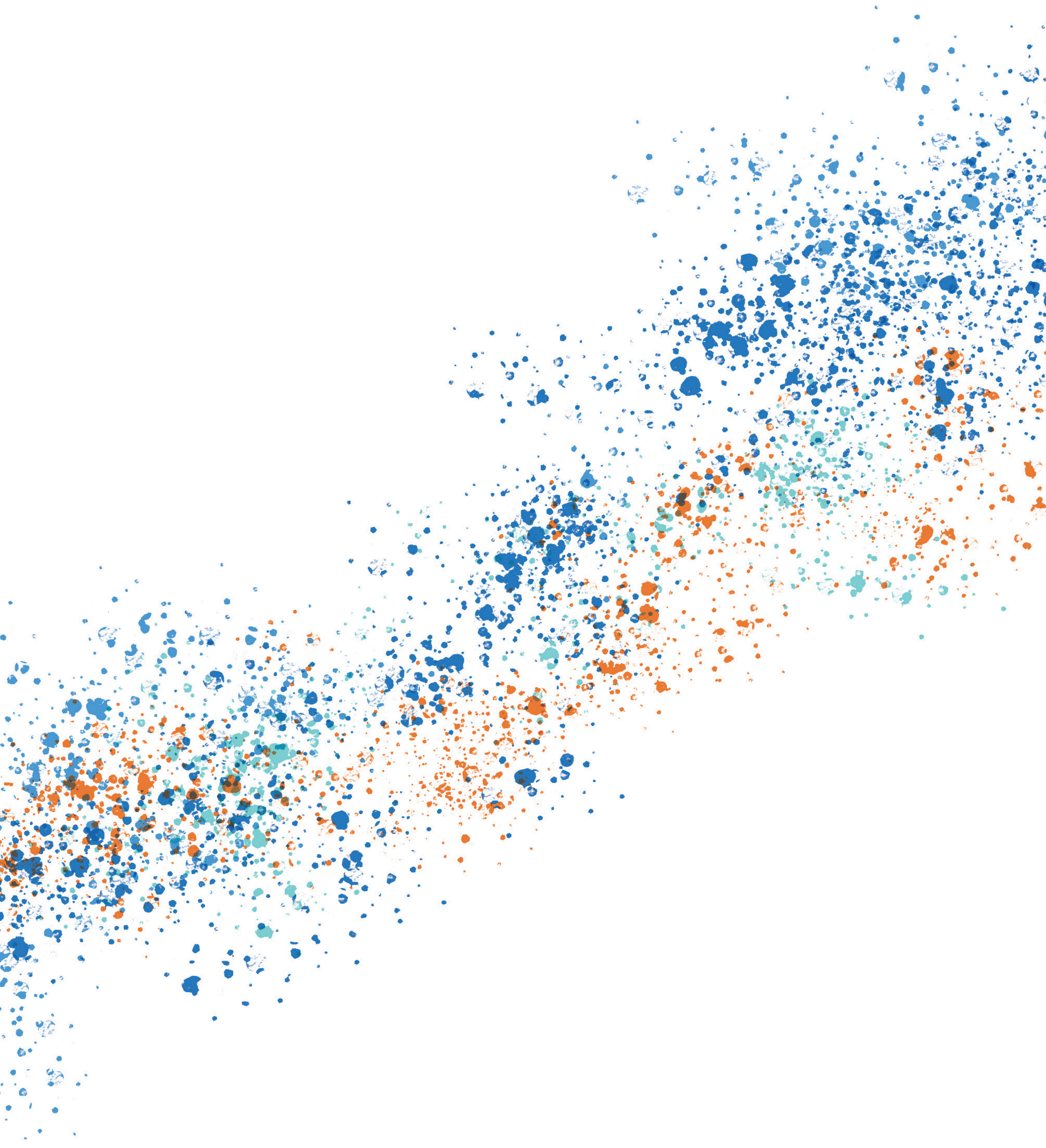

Chapter 5

The importance of reflection and evaluation processes in daily training sessions for progression toward elite level swimming performance

Post, A. K., Koning, R. H., Visscher, C., & Elferink-Gemser, M. T. (2022). The importance of reflection and evaluation processes in daily training sessions for progression toward elite level swimming performance. *Psychology of Sport and Exercise, 61*, [102219]. https://doi.org/10.1016/j.psychsport.2022.102219

Abstract

Self-regulated learning (SRL) involves self-directed metacognitive subprocesses and motivational beliefs that facilitate more effective and efficient learning. We investigated whether youth swimmers who are on track to becoming elite swimmers apply SRL subprocesses more frequently in their daily training sessions compared with swimmers who are not on this track. Insights into swimmers' use of training-centered SRL could advance understanding about underlying individual characteristics that contribute to optimal engagement in daily training and, consequently, progression toward elite level swimming performance. We collected data on training-centered SRL subprocesses (evaluation, planning, reflection, speaking up, effort and self-efficacy) and performance data for 157 youth swimmers aged 12–21 years (73 males and 84 females). The results of a multivariate analysis of covariance revealed significantly higher scores for reflection processes during training for high-performing swimmers but lower scores for effort compared with lower-performing swimmers ($p < 0.05$). A closer examination of the high-performing group showed that those demonstrating greater improvement during a season scored significantly higher for evaluation processes after training compared with those evidencing less improvement during a season ($p < 0.05$). Significant between-group differences in SRL subprocesses remained after adjusting for differences in weekly training hours. Youth swimmers on track to becoming elite swimmers are characterized by more frequent use of reflection processes during training and evaluation processes after training, which suggests that these swimmers' learning and training processes are more effective and efficient. Ultimately, this could contribute to a higher quality of daily training, which may result in greater improvements during a season, higher performance levels, and a greater chance of reaching the level of elite swimming performance.

Keywords

Youth athletes, talent development, acquisition of expertise, self-regulated learning, reflection and evaluation, competitive swimming

Introduction

Youth swimmers who aspire to become elite swimmers must demonstrate outstanding progress (Allen et al., 2014; Post et al., 2020a, 2020b). To reach such expertise, the importance of an extensive period of training is widely acknowledged and usually starts during adolescence or even before (Howe et al., 1998; Starkes 2000). However, not only do aspiring swimmers need to invest in extensive training in terms of quantity (e.g., ~12,000 hours of training, Koninklijke Nederlandse Zwembond [KNZB], 2021), it is also essential that they get the most out of their training sessions in terms of quality (Ericsson et al., 1993; Young et al., 2021). With respect to the latter, self-regulated learning (SRL) is considered as an important variable on athletes' capacity to improve (Elferink-Gemser et al., 2015, Tedesqui & Young, 2015, McCardle et al., 2019). Consequently, SRL is an intriguing concept in the study of underlying individual characteristics that contribute to progression toward elite level swimming performance.

SRL indicates the extent to which individuals are metacognitively, motivationally and behaviorally proactive in their own learning processes (Zimmerman 1986, 2006). Conceptually, it refers to an individual's engagement in a set of psychological subprocesses and beliefs that (1) makes them think about their own thinking (meta-cognitive processes like evaluation and reflection) and (2) motivates them to engage in meta-cognitive and behavior control (e.g. through effort and self-efficacy; Zimmerman, 2011). Zimmerman's (2000) social-cognitive SRL model, which is the most commonly used model in the SRL literature, posits that these subprocesses and beliefs fall into three structurally interrelated and cyclically sustained phases: the forethought phase (before learning), the performance phase (during learning) and the self-reflection phase (after learning). Feedback from prior performances (the self-reflection phase) is applied during the forethought phase to make adjustments for current and future efforts (the performance phase), thus completing a self-regulatory cycle (Ertmer & Newby, 1996; Zimmerman, 2000).

It has been posited that engagement in SRL subprocesses and beliefs increase learners' awareness and control of the functional relationships between their patterns of thought and action, and outcomes in the real-world (Zimmerman, 1986). Learners who set clear goals, formulate a plan to practice, monitor the strategy's implementation, and evaluate practice outcomes to adjust subsequent behavior or goals, gain clarity on what they want to achieve, what they have to do to achieve their self-designated goals, what they should actually do during practice, and the effectiveness of their thoughts, strategies, and actions. Consequently, they acquire a better understanding of what can be learned from past performances in order to improve current and future performances. Thus, SRL is thought to help individuals to learn more effectively and efficiently (Zimmerman, 1986, 2006; Jonker et al., 2010a), which is major source of motivation for continued self-regulation and investment of effort in the learning process (Zimmerman & Paulsen, 1995; Bandura, 1997)

Effective and efficient acquisition of knowledge and skills is highly desirable in competitive, globalized sports, such as competitive swimming. Given the restricted number of daily training hours (work-rest ratio), the limited time available to make it to the top (with advancing age) and the ongoing increase of the international performance standards, it is important for aspiring swimmers to gain maximal benefits from training and competition. Engagement in SRL may enable ambitious swimmers to optimize their developmental process. As such, effective SRL may be an indirect but crucial factor for acquiring sport expertise (Zimmerman, 2006; McCardle et al., 2019).

The association between SRL and the attainment of sport expertise is supported by several studies that investigated differences in SRL among skill-based groups. For example, Cleary and Zimmerman (2001) found that expert youth basketball players set more specific goals, selected more technique-oriented strategies, were more strategic, and displayed higher levels of self-efficacy than non-experts and novices. Jonker et al. (2010a, 2010b) and Toering et al. (2009) highlighted the importance of reflection skills in relation to performance levels. Both studies found that advanced youth athletes outscored their lower-level peers in the area of reflection. Moreover scores for reflection were higher for athletes who made the transition from junior national to senior international level (Jonker et al., 2012) and distinguished junior international athletes from junior national athletes (Jonker et al., 2010a; Toering et al., 2012). Bartulovic et al. (2017), who studied senior athletes, showed that elite status was most strongly associated with engagement in overall SRL and self-monitoring. In sum, these studies unanimously suggest that expert athletes engage more frequently and in more sophisticated SRL subprocesses than less proficient or novice athletes.

However, it is noteworthy that the SRL concept has been studied and measured in various ways within the SRL literature (see review McCardle et al., 2019). For example, Cleary and Zimmerman (2000) assessed meta-cognitive processes of SRL using a microanalytic approach (an examiner asked a set of questions during practice and participants responded orally). Their questions about SRL, which solely related to free throws in basketball (domain-specific), were focused on one task of short duration (microscopic-level) within a training session and were about specific instances (event) with a temporally defined beginning and end. By contrast, Toering et al. (2009, 2012a) and Jonker et al. (2010a, 2010b,2012) measured six SRL subprocesses (planning, monitoring, evaluation, reflection, self-efficacy and effort) using the Self-Regulation of Learning Self-Report Scale (SRL-SRS) questionnaire (Toering et al., 2012b) which also included motivational aspects of SRL. In these studies, questions about SRL were related to the overall learning context (domain-general) and focused on broader, longer-term regulation across multiple learning sessions (macroscopic-level). Moreover, they assessed the frequency of engagement in SRL subprocesses as a relative enduring, aptitude-based characteristic. Inspired by this line of research, Toering et al. (2013) and Bartulovic et al. (2017) developed sport-specific SRL questionnaires, initializing the recent trend in SRL research in which SRL is proposed to be a more sport-specific skill rather than a domain-general disposition (Reverberi et al. 2021). Moreover, they argued that SRL measures should focus on everyday sports practice sessions in order to provide meaningful results that could contribute to a better understanding of sport-related performance development.

Accordingly, we suggest that besides the more training-centered and sport-specific focus in SRL, an additional shift in research is needed. Whereas most SRL studies in sport have focused on the relationship between SRL and athletes' performance levels, there has been little attention to how SRL relates to performance progression (Elferink-Gemser et al., 2015). Establishing a link between SRL and performance progression could be a crucial step towards advancing understanding of the development of sport expertise. For example, previous studies on competitive swimming have shown that youth swimmers who are on track to becoming elite swimmers (i.e. top 50 swimmers worldwide) are characterized by higher performance levels (Post et al. 2020a) and progression within a season (Post et al., 2020b). However, the underlying individual characteristics that contribute to the actual progression of an individual from one performance level to another remain unclear. Therefore, a question that arises is whether differences in training-centered SRL are associated with differences in performance levels and progression in competitive swimming. By investigating individuals' training-centered SRL in relation to their performance levels and progression, we may acquire a better understanding of underlying individual characteristics that contribute to optimal engagement in daily training sessions and consequently to progression toward elite level swimming performance. Therefore, knowledge about training-centered SRL in competitive swimming may be of value for enhancing the effectiveness and efficiency of talent development programs.

The present study was aimed at extending the body of SRL research in relation to the performance levels and progression of youth swimmers, using a sport-specific, aptitude-based questionnaire (Toering et al., 2013) focusing on daily training sessions. We sought to answer the question of whether youth swimmers who are on track to reach the elite level apply SRL more frequently in their daily training sessions compared to swimmers who are not on this track. Consequently, we investigated training-centered SRL in advanced competitive swimmers who differed in (a) their performance levels and (b) their performance progression within a season. Despite the theoretical and practical implications, there is a lack of studies combining training-centered SRL with these performance measures.

Our investigation comprised two parts. First, we examined differences between high-performing and lower-performing swimmers relating to their use of training-centered SRL (part one). Second, focusing specifically on high-performing swimmers, we examined differences in the use of training-centered SRL by swimmers whose progress was advanced and those whose progress was less advanced (part two). We hypothesized that (a) high-performing swimmers obtained higher scores for training-centered SRL than lower-performing swimmers (part one) and (b) swimmers whose performance progress was advanced obtained higher scores for training-centered SRL than those whose progress was less advanced (part two).

Methods

Ethical approval

All participants were informed of the study's procedures prior to their participation and provided their written informed consent to participate. Informed consent was also obtained from parents of participants who were below 16 years old. All procedures used in the study complied with the Helsinki Declaration and were approved by the research ethics committee of the University Medical Center Groningen, University of Groningen, The Netherlands (202000488).

Data collection

A total of 157 Dutch competitive swimmers (73 males and 84 females) aged 12-21 years were included in the present study. All swimmers had participated in the National Dutch Junior Championships ("Nederlandse Junioren & Jeugd Kampioenschappen"; n = 125) and/or were selected for talent development programs (n = 33) organized by the KNZB. We collected data on the use of training-centered SRL and swim performances of these swimmers during the 2018/2019 swim season (see Figure 1). The season, which was officially launched on September 1, 2018 and ended August 31, 2019 (Fédération Internationale de Natation [FINA], 2021), comprised a short course season (September - December in the 25 m pool) and a long course season (January - August in the 50 m pool).

Cross-sectional data on training-centered SRL were collected using an online survey instrument (Qualtrics, Provo, UT) one month before the start of the long course swim season (December 2018). Longitudinal data on long course swim performances for all strokes and distances (swim events) were obtained from Swimrankings (2021) during the long course swim season (January 2019 – August 2019). Swimmers were divided into age groups according to their age on December 31, 2018 (KNZB, 2021). Therefore, all ages in the present study refer to the age categories in which swimmers participated during the 2018/2019 swim season and not to the swimmers' calendar ages.

Swimmers were included in the present study if they (1) were 12 years or older, (2) had completed the questionnaire in December 2018, and, if (3) information on swim performances for the 2018/2019 swim season was available.

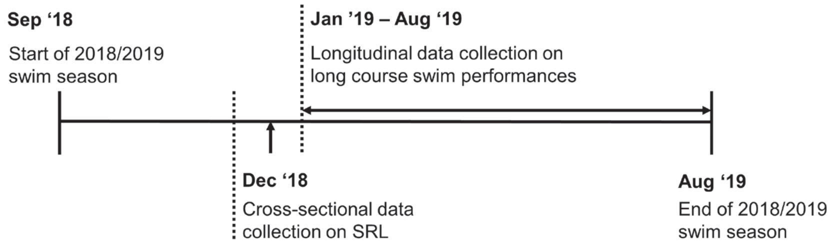

Figure 1. Schematic timeline of the data collection procedure.

Note. The vertical arrow indicates the moment of cross-sectional data collection on training-centered SRL. The horizontal arrow indicates the time period in which longitudinal data collection of long course swim performances took place.

Survey measures

The online questionnaire comprised three sections: general items, sport-specific items and SRL-related items.

General items

In the first section of the questionnaire, swimmers provided their personal details (e.g., date of birth and sex).

Sport-specific items

In the second section, swimmers responded to sport-specific items on their training sessions (e.g., the number of weekly training sessions, the number of hours of weekly swimming training, and their sport history).

SRL-related items

In the third section, six SRL subprocesses were assessed using various existing questionnaires (Toering et al., 2012b, 2013). We included items on processes of evaluation (6 items), planning (5 items), reflection (9 items) and speaking up – which can be considered as a SRL strategy (6 items), to measure the meta-cognitive aspect of SRL. Our instrument for measuring meta-cognitive SRL was based on the football-specific SRL questionnaire developed by Toering et al (2013). Respondents rated items using a 5-point Likert scale (1 = *never*, 2 = *seldom*, 3 = *sometimes*, 4 = *often*, 5 = *always*). Examples of items were as follows. Evaluation: "After each practice session, I think back and evaluate whether I did the right things to reach my practice goal." Planning: "Before each practice session, I plan my actions relative to the goal I want to attain during the practice session." Reflection: "During each practice session, I try to identify my strengths and think about ways to improve these even more." Speaking up: "If the coach changes an exercise and I don't understand the change, I ask the coach to explain."

The football-specific self-regulated learning questionnaire was developed as a self-report instrument to measure SRL used in daily football practice. Small adjustments were made to use the questionnaire in competitive swimming. Football-related terms (i.e. "football player" and "football skills) were replaced with swimming-related terms ("i.e. "swimmer" and "swimming skills"). Two planning items were removed because they did not apply to competitive swimming (e.g., "After each practice session, I stay to work on specific skills.") For the same reason, coaching-related items in the football-specific SRL questionnaire were not included in the present study.

Items on processes of self-efficacy (10 items) and effort (9 items) were included to measure the motivational aspect of self-regulation. The instrument for measuring motivational SRL processes was derived from the SRL-SRS questionnaire developed by Toering et al. (2012) and responses were scored using a 4-point Likert scale (1 = *almost never*, 2 = *sometimes*, 3 = *often*, 4 = *almost always*). Examples of items are as follows. Effort: "I put forth my best effort when performing tasks." Self-efficacy: "I am confident that I can deal efficiently with unexpected events."

Following Toering et al. (2013) we assigned five of the six SRL subprocesses to one of the three sequential phases of daily practice: before practice, during practice, or after practice. Planning aspects pertained to the time before training; aspects relating to speaking up, reflection and effort pertained to the time during training; and evaluation aspects pertained to the time after training. Self-efficacy was not confined to a particular training phase. **Appendix A** lists all SRL items in our questionnaire. Cronbach's α coefficients were calculated to determine the internal consistency of the measurements of the six SRL subprocesses. Measurements of all SRL subprocesses met the criterion value of $\alpha > 0.70$ (α between 0.75 – 0.89; Nunnally, 1978). The inter-scale correlations were calculated with Spearman correlations and did not exceed a value of 0.80 (r_s between 0.21- 0.75; see **Appendix B**; Carron et al., 1985).

Performance measures

We collected longitudinal data on individual swimmers' performances for multiple swim events, which necessitated the use of a method for comparing swim performances between swim events to define the best swim performance of the 2018/2019 swim season. The method that we used was introduced by Stoter et al. (2019) in the context of speed skating and has also been applied in competitive swimming (Post et al., 2020a, 2020b).

Following this method, we linked swimming to the prevailing world record (WR) during the 2018/2019 swimming, known as relative Swim Time (rST). The rST denotes the absolute swim time as a percentage of the world record. In this study, rST was used to define swim performance (see equation 1).

$$\text{relative swim time (rST)} = \left(\frac{\text{swim time}}{\text{world record}}\right) * 100\% \qquad \text{(eq. 1)}$$

Referring to the rST, we determined the best swim event of the season for each swimmer. The best seasonal swim event was defined as the swim event with the lowest rST, reflecting the swim performance closest to the prevailing WR. Only the longitudinal data on the best seasonal swim event was selected for further analyses.

Defining performance level groups (part one)

In part one of the present study, swimmers were divided into two groups according to their performance levels: a high-level performance group or a lower-level performance group. We defined groups according to performance trajectories of international elite swimmers, representing the top 50 swimmers worldwide (FINA, 2021). Following Post et al. (2020a), we used the slowest seasonal best swim performance by age category, sex and swim event of these international elite swimmers as performance benchmark (maximum season's best rST per age category, sex and swim event). Swimmers whose seasonal best performances (season's best rST) fell within the performance benchmark were defined as high-level performers (n = 92). Conversely, those swimmers whose swim performances were not fast enough were defined as lower-level performers (n = 65; see Figure 2).

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Defining performance progression groups (part two)

Part two of the present study included solely swimmers of the high-level performance group of part one with at least two recorded swim performances in their seasonal best swim event during the 2018/2019 swim season. Therefore, out of the total sample of 157 swimmers, 89 swimmers (49 males and 40 females) aged 12-20 years were included for further analysis (see Figure 2). These 89 swimmers were divided into an advanced progression group and a less advanced progression group, according to their progression level within a season.

Applying the method of Post et al. (2020b), we calculated the within-season performance progression of these swimmers during the period between the first swim performance of the season (first rST) and the season's best rST (see equation 2). Again, we defined groups according to performance trajectories of international elite swimmers, representing the top 50 swimmers worldwide (FINA, 2021). The mean performance progression within a season of these international elite swimmers aged 12–21 years (by sex and swim event) was used as a progression benchmark for categorizing swimmers as advanced progressors or less advanced progressors (Post et al., 2020b). Swimmers who progressed as much as or more than the progression benchmark were defined as advanced progressors (n = 23), whereas swimmers whose progress did not reach the progression benchmark were defined as less advanced progressors (n = 66, see Figure 2). Youth swimmers in the advanced progression group (12 males and 11 females) were considered to be on track to becoming elite swimmers (i.e., belonging to the top 50 swimmers worldwide).

$$\text{performance progression within the season} = -\left(\frac{\text{current season's best rST} - \text{first rST}}{\text{first rST} - 100}\right) * 100\%$$

(eq. 2)

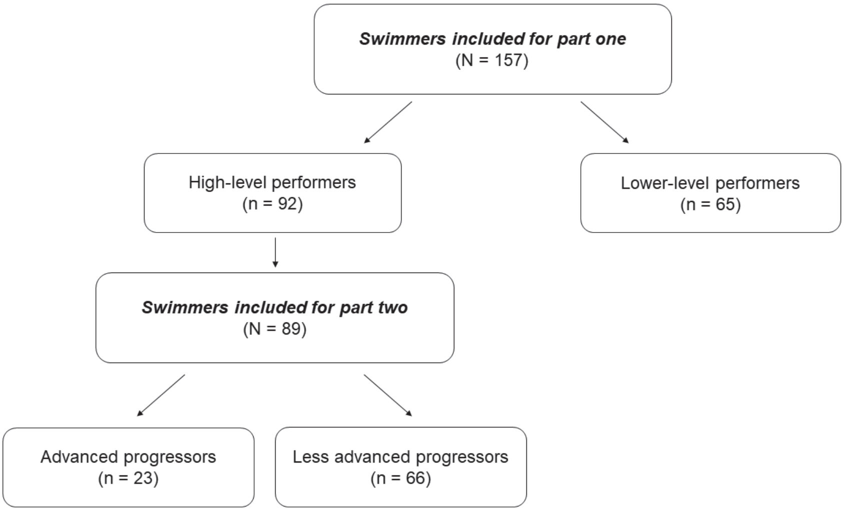

Figure 2. Schematic representation of the study sample.

Statistics

All data were analyzed using R (R Core Team, 2019). Descriptive statistics (mean scores and SDs) were calculated for the six self-regulation processes for (a) high-level performers and lower-level performers (part one) and (b) advanced and less advanced progressors (part two). To interpret the scores, effect sizes (Cohen's d values) were calculated. An effect size of approximately 0.20 was considered small, while effect sizes of 0.50 and 0.80 were considered moderate and large, respectively (Cohen, 1988).

Referring to the previous literature (see Jonker et al., 2011) and our own data, we conducted a preliminary multivariate analysis of variance (MANOVA), which showed that the engagement in SRL subprocesses was significantly related to weekly training hours but not to age and sex. Therefore, weekly training hours were included as covariates in the analyses conducted for both studies.

We included a multivariate analysis of covariance (MANCOVA) to examine differences in the application of SRL processes between (a) high-level and lower-level performers (part one) and (b) advanced and less-advanced progressors (part two). Pillai's trace was used as a test statistic. The six SRL processes were the dependent variables, performance level group (part one) or performance progression group (part two) was the independent variable, and weekly training hours was the covariate. When appropriate, a univariate analysis of covariance (ANCOVA) was separately performed on each of the dependent variables, with performance level group (part one) or performance progression group (part 2) as the independent variable. For the MANCOVA, $p < 0.05$ (two-tailed) was set as the significance level. For the ANCOVA, $p < 0.05$ (one-tailed) was set as the significance level.

A sensitivity power analysis using G* Power (Faul et al., 2007, 2009) confirmed that our statistical tests were sufficiently sensitive to detect significant differences with an effect size of 0.45 (study purpose 1) and of 0.60 (study purpose 2) (alpha = 0.05, power = 0.80). Statistical tests for measuring invariance were not performed given the nature of our dataset (relatively few observations for many items).

Results

Table 1 shows the descriptive characteristics according to performance level and progression (92 high-level performers; 65 lower-level performers; 23 high progressors, 66 lower progressors). Tables 2 and 3 show the mean scores and standard deviations for the six SRL subprocesses for performance level and progression groups and the corresponding effect sizes.

SRL subprocesses and performance level (part one)

The MANCOVA analysis revealed significant differences for performance level groups ($F_{(6,149)}$=2.659; p <0.05). The ANCOVA showed that high-level performers significantly outscored lower-level performers on reflection ($F_{(1,154)}$=3.067; p <0.05, d=0.28). Moreover, the scores for effort of high-level and lower-level performers differed significantly, with the former having lower scores than the latter ($F_{(1,154)}$ = 3.354; p < 0.05, d = 0.29). No significant differences between the two performance level groups were observed for evaluation ($F_{(1,154)}$=0.382), planning ($F_{(1,154)}$=1.041), speaking up ($F_{(1,154)}$=2.001), and self-efficacy ($F_{(1,154)}$=0.583), (all p >0.05 with small effect sizes). Covariate weekly training hours were significant, indicating that swimmers who expended more weekly training hours reported higher scores for SRL subprocesses ($F_{(6,149)}$=3.018; p <0.01).

SRL subprocesses and performance progression (part two)

The results of the MANCOVA analysis revealed significant differences for performance progression groups ($F_{(6,80)} = 3.451$; $p < 0.01$). The ANCOVA analysis showed that the scores of advanced progressors were significantly higher than those of less advanced progressors for evaluation ($F_{(1,85} = 3.611$; $p < 0.05$, $d = 0.47$). No significant differences between the two performance progression groups were observed for reflection ($F_{(1,85} = 0.219$), planning ($F_{(1,85} = 1.031$), speaking up ($F_{(1,85} = 0.167$), effort ($F_{(1,85} = 0.246$), and self-efficacy ($F_{(1,85} = 0.495$) (all $p > 0.05$ with small effect sizes). Covariate weekly training hours were not significant ($F_{(6,80)}$=1.040; p >0.05).

Table 1. Characteristics of swimmers according to performance level and progression (N = 157).

	Performance level groups (N = 157)				**Performance progression groups (N = 89)**			
	Lower-level performers (n = 65)		High-level performers (n = 92)		Less advanced progressors (n = 66)		Advanced progressors (n = 23)	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Age (years)	15.0	1.9	15.1	2.0	14.9	1.6	16.0 *	2.0
Swim training (hours per week)	9.8	3.8	11.2 *	4.4	10.8	4.4	12.7 *	3.9
Season's best rST (%)	123.4	8.2	117.3 *	7.6	118.7	7.5	112.8 *	6.1
Performance progression (%)	-	-	-		16.3	7.0	37.8 *	9.0

Note. Means (M) and standard deviation (SD) values for age, swim training hours per week and performance measures according to performance level and performance progression.
* p < 0.05 (one-tailed)

Table 2. Descriptive statistics for all self-regulated learning (SRL) subprocesses applied by swimmers according to performance level (N = 157).

	Lower-level performers (n = 65)		**High-level performers (n = 92)**		**Effect sizes**
	M	*SD*	*M*	*SD*	*d*
Evaluation •	3.27	0.81	3.33	0.71	0.07
Planning •	3.26	0.97	3.39	0.91	0.15
Reflection •	3.42	0.79	3.61 *	0.60	0.28
Speaking up •	3.80	0.64	3.93	0.48	0.24
Effort ♦	3.55	0.33	3.44 *	0.41	0.29
Self-efficacy ♦	3.19	0.46	3.24	0.41	0.13

Note. Means (M) and standard deviation (SD) values for all self-regulated learning (SRL) subprocesses according to performance level.
• meta-cognitive subprocesses were measured using a 5-point Likert scale (range 1 – 5)
♦ motivational subprocesses were measured using a 4-point Likert scale (range 1 – 4)
* p < 0.05 (one-tailed)

Table 3. Descriptive statistics for all self-regulated learning (SRL) subprocesses for high-level performers according to performance progression within a season (N = 89).

	Less advanced progressors (n = 66)		**Advanced progressors (n = 23)**		**Effect sizes**
	M	*SD*	*M*	*SD*	*d*
Evaluation •	3.26	0.79	3.58 *	0.31	0.47
Planning •	3.46	0.96	3.25	0.75	0.23
Reflection •	3.61	0.64	3.68	0.42	0.11
Speaking up •	3.92	0.52	3.96	0.36	0.09
Effort ♦	3.47	0.43	3.35	0.35	0.29
Self-efficacy ♦	3.22	0.42	3.28	0.39	0.16

Note. Means (M) and standard deviation (SD) values for all self-regulated learning (SRL) subprocesses according to performance progression.
• meta-cognitive subprocesses were measured using a 5-point Likert scale (range 1 – 5)
♦ motivational subprocesses were measured using a 4-point Likert scale (range 1 – 4)
* $p < 0.05$ (one-tailed)

Discussion

We investigated training-centered SRL subprocesses in relation to performance levels and performance progression within a season of youth swimmers aged 12-21 years. After controlling for differences in weekly training hours, we found that swimmers in the high-level performance group scored significantly higher on reflection during training but significantly lower on effort than swimmers in the lower-level performance group (part one). Furthermore, a closer examination of the high-level performance group showed that those demonstrating greater improvement during the season significantly used evaluation processes after training more frequently compared with those evidencing less improvement during the season (part two). To the best of our knowledge, the present study is the first to investigate this combination of performance variables and SRL measures, providing new insights into the role of training-centered SRL in the development of swim expertise.

Our study provides an answer to the key question of whether youth swimmers who are on track to reach the elite level use SRL subprocesses more frequently during their daily training sessions than do those who are not on this track. An important matter while addressing this question is the way performance groups are defined, given that a different classification of performance groups may lead to different outcomes (Swann et al., 2015). It is noteworthy that we defined performance groups according to performance trajectories of international elite swimmers (i.e., the top 50 swimmers worldwide). Therefore, swimmers in the advanced progression group were youth swimmers who were considered to be on track of becoming elite swimmers (i.e., their performances and progression were at the benchmark levels). In other words, these swimmers are considered to have the potential to make it to the top 50 swimmers worldwide. When studying such talented swimmers, traditional null hypothesis testing may be limited due to small sample sizes, which are characteristic for elite sport (Skorski & Hecksteden, 2021). This could lead to insufficient power to detect significant differences with small effect sizes. Consequently, a small change in a variable may be interpreted as having no effect. However, small changes may be practically meaningful, especially in this research field (Gabbett et al., 2017). Therefore, in the interpretation of our results, effect sizes are of particular relevance as they convey the magnitude of the effect (Nuzzo, 2014). Another key point in our analyses is that we corrected for differences in weekly training hours, so that between-group differences in SRL subprocesses referred to differences in the individual characteristics of swimmers rather than to the consequences of more hours in training. Considering our methodological choices and statistical outcomes, we argue that youth swimmers who are on track to becoming elite swimmers are characterized by more frequent use of reflection processes during training (small to medium effect sizes) and evaluation processes after training (small to medium effect sizes).

In line with previous studies of Jonker et al. (2010a, 2010b, 2012) and Toering et al. (2009, 2012), our findings support the notion that reflection processes contribute to more efficient learning and, consequently, to the attainment of higher performance levels. Here, reflection refers to the ability to learn by looking back critically on previous performances and to use new information in subsequent learning situations for self-improvement (Jonker et al., 2012). Our findings not only showed that swimmers in the high-level performance group significantly engaged more frequently in reflection processes during training compared with those in the lower-level performance group, but they also showed that these swimmers scored significantly lower (but still relatively high) for willingness to invest effort. In other words, high-performing swimmers seem to get more out of their training even though they put in relatively less work compared with swimmers who perform at a lower level. A possible explanation could be that high-performing swimmers who frequently engage in reflection during their training sessions carefully assess which tasks to expend effort in rather than expending effort in all situations. As a result, they may train more efficiently (Jonker et al., 2011). The ability to distinguish between what is important (main issues) and what is less important (side issues) is essential for achieving further progress toward goal attainment. Nevertheless, it is important to note that scores for effort were relatively high for all swimmers in our study. This finding, which is in line with findings of other studies (e.g., Jonker et al., 2010a, Toering et al., 2009), accords with the idea that youth athletes who aspire to make it to the top must be willing to expend maximal efforts (Ericsson et al., 1993). However, our findings highlight the importance of directing those efforts towards relevant tasks that contribute to performance development (Stam et al., 2020). Put differently, effort is evidently important but it is not enough. Moreover, our findings showed that high-performing swimmers tended to score higher on evaluation, planning, self-efficacy (negligible effect sizes), and speaking up (small to medium effect sizes), although these results were not statistically significant. Therefore, supported by our results, we argue that the engagement in training-centered SRL, and especially the frequent use of reflection during training sessions, is a fundamental characteristic of swimmers who are on track to becoming elite swimmers.

In addition to reflection, another notable SRL subprocess that seems to be typical for swimmers who are on track to reach the elite level is evaluation. We found that among high-performing swimmers, those who demonstrated more improvement within a season used evaluation processes after training more frequently compared with those who showed less improvement. Here, it is important to note that all high-performing swimmers demonstrated similar performance levels at the start of the season, but differed in their performance progression during the season. Consequently, their performance levels varied at the end of the season. Though advanced progressors tended to score higher for reflection, self-efficacy, and speaking-up (negligible effect sizes) and lower for planning and effort compared with less advanced progressors, evaluation was the only SRL subprocess that reached significance. Therefore, performance progression within a season seems to be related especially to evaluation after training, which is striking. According to Zimmerman (2000), evaluation is a subprocess of reflective thinking that is related to the result (self-judgement) rather than to a standard or goal (self-reaction). In particular, evaluation refers to the ability to assess both the learning process and the result achieved after task execution (Jonker et al., 2010b). The assessment of training outcomes in light of attainment goals may be a crucial starting point for further improvement. Swimmers who evaluate their training outcomes more frequently after training may, as a consequence, be better able to correct for weaknesses in their training program, and make appropriate adjustments in their training behavior or goals, thereby, achieving greater improvements during a season. In essence, evaluation processes may contribute to more effective learning.

A striking finding is that the meta-cognitive processes related to differences in the swimmers' performance levels and progression occurred during the same phase of the SRL cycle, namely the self-reflection phase. However, reflection and evaluation processes relating to daily training sessions, as measured in the present study, were assigned to different moments in time (before, during, and after training). These observations highlight two key points, namely the prominent role of the self-reflection phase in the SRL cycle relating to performance development and the dimension-transcending nature of SRL. Hence, we are well aware that swimmers may also use the same SRL subprocesses during other phases of the learning, training, or developmental processes (e.g., reflective processes after training and evaluative processes during training) that we did not measure. In light of our assessment of the swimmers' engagement in SRL before, during, and after training, we concluded that those swimmers who are on track to reach the elite level not only engage more frequently in SRL subprocesses during training (reflected, for example, in higher reflection scores) but also post-training (reflected, for example, in higher evaluation scores). Therefore, we suggest that the capacity to derive more from training may extend beyond the actual training time spent in the pool.

The present study sheds light on a unique and specific aspect of the SRL concept in relation to sports. However, it is important to realize that SRL is a dynamic, multidimensional construct, which can be viewed, measured, and applied across different dimensions (see the review of McCardle et al., 2019). Consequently, our findings relate to how we approached SRL: as a domain-specific aptitude (i.e., the consistency of SRL processes in competitive swimming) applied during daily training sessions (temporal framing). This means that specific SRL subprocesses are measured during specific phases of the training process (e.g., reflection processes are measured during a training session, whereas evaluation processes are measured after a training session). We believe that when used in combination with the included performance variables, and when corrections are made for differences in weekly training hours, the theoretical and practical relevance of our SRL approach is apparent, advancing understanding of progression toward elite level swimming performance.

From a theoretical perspective, the finding that training-centered SRL is not only related to performance level but also to progression within a season, provides an important link between the SRL framework and athletes' development of expertise. Whereas previous studies mainly promoted the idea that self-regulating athletes are able to derive more from training and likely to reach higher performance levels, our findings add to the body of literature, suggesting that performance progression within a season is an important link in understanding this relation. We found that high-performing swimmers who demonstrate greater improvements during a season (i.e. are on track to becoming elite swimmers) are characterized by more frequent use of reflection and evaluation processes in their daily training sessions. These individual characteristics are considered to contribute to more effective and efficient learning (and training), which may explain why these swimmers improve more during a season and, consequently, reach higher performance levels.

Therefore, the present study contributes not only to a deeper understanding of the individual characteristics relating to advancement toward swimming expertise but it also sheds light on the potential underlying mechanisms that may partly explain why higher scores for SRL subprocesses are ultimately related to higher performance levels. This finding is strengthened by the finding that between-group differences in reflection and evaluation processes remained significant after controlling for differences in weekly training hours. Therefore, we suggest that swimmers who are on track to attain the elite level are able to get more out of their training in terms of quality and ultimately to benefit more from this ability by practicing for more hours in a week (see Table 1). These conclusions are in alignment with the theory of deliberate practice (DP; Baker et al., 2003; Deakin & Cobley, 2003; Ericsson et al., 1993)

Pursuing this line of reasoning, we suggest that future studies should examine the causal relationships among training-centered SRL, the quantity and quality of DP, and the development of sport expertise (McCardle et al., 2019). However, a number of issues need to be addressed beforehand. First, there is considerable inconsistency in the measurement of SRL subprocesses using subscales in self-reported questionnaires. For example, we used items describing the self-monitoring processes that were applied by Bartulovic et al. (2017) to measure reflection processes during training. Moreover, we used a 4-point and 5-point Likert scale to measure SRL subprocesses, whereas Bartulovic et al. (2017) applied a 7-point Likert scale. Such refined scale is recommended for future studies, as it could increase the power of statistical tests and, thus, the sensitivity to detect significant differences, also with small effect sizes (Wasserstein & Lazar, 2016). The inconsistency in the measurement of SRL subprocesses makes it difficult to compare findings between studies. However, this issue is not new in the literature on elite sports (see Swann et al., 2015) and psychology (see Dohme et al., 2017) and a similar approach (e.g., a systematic review) could help to create more consistency and common ground in the measurement of SRL subprocesses.

Second, there is a further need to develop reliable and valid methods for mapping the quantity and quality of DP (Baker et al., 2020). To establish causal relationships between SRL, DP and performance development, variables such as weekly training hours should be further specified in terms of DP. Moreover, given that SRL is considered as a factor that contributes to the quality of DP, it would be interesting not only to examine the quantity of training-centered SRL subprocesses (as in the present study) but also their quality. For example, reflection and evaluation processes could be analyzed in relation to goal-setting and goal-evaluation standards. Finally, the present study was the first to introduce both performance level and performance progression measures in SRL. However, we were unable to include longitudinal data on SRL because of COVID-19 restrictions. Rather than cross-sectional research, longitudinal studies extend beyond a single moment in time and measure within-person change. This can enhance our understanding of how phenomena unfold over time and is a prerequisite to draw causal inferences (Stenling et al., 2017). Given the significant developmental changes that occur in maturing swimmers, the inclusion of longitudinal data would have been highly relevant for advancing the understanding of how age and developmental status could impact on the engagement and value of SRL in sport. Therefore, when studying the development of sport expertise, we call for the inclusion of longitudinal data on all key parameters (SRL, DP, and performance measures) in future studies. Such longitudinal studies could further examine whether SRL is an underlying individual characteristic with predictive value for future elite swimming performances.

Practical Implications

Given time constraints that affect the trajectory for reaching elite status, it is essential to get the most out of each training, especially in a competitive, globalized sport like competitive swimming. Therefore, effective and efficient learning (and training) is fundamental for swimmers who aspire to make it to the top. Consequently, it could be valuable to monitor and develop SRL subprocesses, especially those relating to reflection and evaluation, during daily training sessions. The more frequent use of these SRL subprocesses are shown to be characteristic for swimmers who improved more during a season and reached higher performance levels. Therefore, coaches could encourage swimmers to reflect more frequently on their strengths and weaknesses during training sessions and to assess their training outcomes in relation to the attainment of their goals after training. Moreover, coaches could help swimmers to focus and expend effort on the main tasks that matter most rather than on side tasks that are less important. Finally, coaches and swimmers should be aware that effective and efficient learning is an ongoing process, which does not necessarily stop after the training session ends.

Conclusion

The results of this study have shown that swimmers who are on track to becoming elite swimmers are characterized by higher scores on reflection and evaluation processes entailed in daily training sessions. The more frequent use of SRL subprocesses during and after training among swimmers who are on track to reach the elite level suggests that they learn and train in a more efficient and effective way. Moreover, our findings suggest that, compared with their peers, these swimmers may benefit more from training because they are more actively involved in their learning process both in and out of the water. Ultimately, this proactive involvement could contribute to a higher quality of daily training, which may result in greater improvements during a season, higher performance levels, and a greater chance of reaching the level of elite swimming performance.

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Appendices

Appendix A. Items for each self-regulated learning (SRL) subprocess.

SRL subprocess	Items
Evaluation	Each practice session I think back and evaluate whether I did the right things to become a better swimmer.
	After each practice session I think back at situations I've been through during practice and use this information to practice specific situations either alone or together with others.
	Each practice session I keep track of my performance during practice, so that I can see which swim skills I must improve (for example, technique, tactics).
	After each practice session I think back and evaluate whether I did the right things to reach my practice goal.
	After each practice session I think about what I did right and wrong during the session.
	After each practice session I think back at specific practice situations and what I did right and wrong.
Planning	I have a clear goal for each practice session.
	Before each practice session I plan which skills I want to work on during the session.
	Each practice session I use information from TV/internet/live swim matches to become a better swimmer.
	Before each practice session I plan my actions relative to the goal I want to attain during the practice session.
	Each practice session I use information from books, magazines, and interviews about elite swimmers to develop myself as a swimmer.
Reflection	Each practice session I think about both my strengths and weaknesses and of ways that I can improve them.
	During each practice session I check whether I make progress in my swimming skills.
	I know my strengths and weaknesses and at each practice session I plan how I can improve them.
	During each practice session I keep track of my swim performance relative to my practice goal (so that I know where I stand).
	Each practice session I try to identify my strengths and think about ways to improve these even more.
	Each practice session I work on my strengths and weaknesses because I believe in my potential as a swimmer.
	Each practice session I focus on my practice goal.
	During each practice session I check what I still have to do to reach my practice goal.
	Each practice session I try to identify my weaknesses and think about how to improve these.

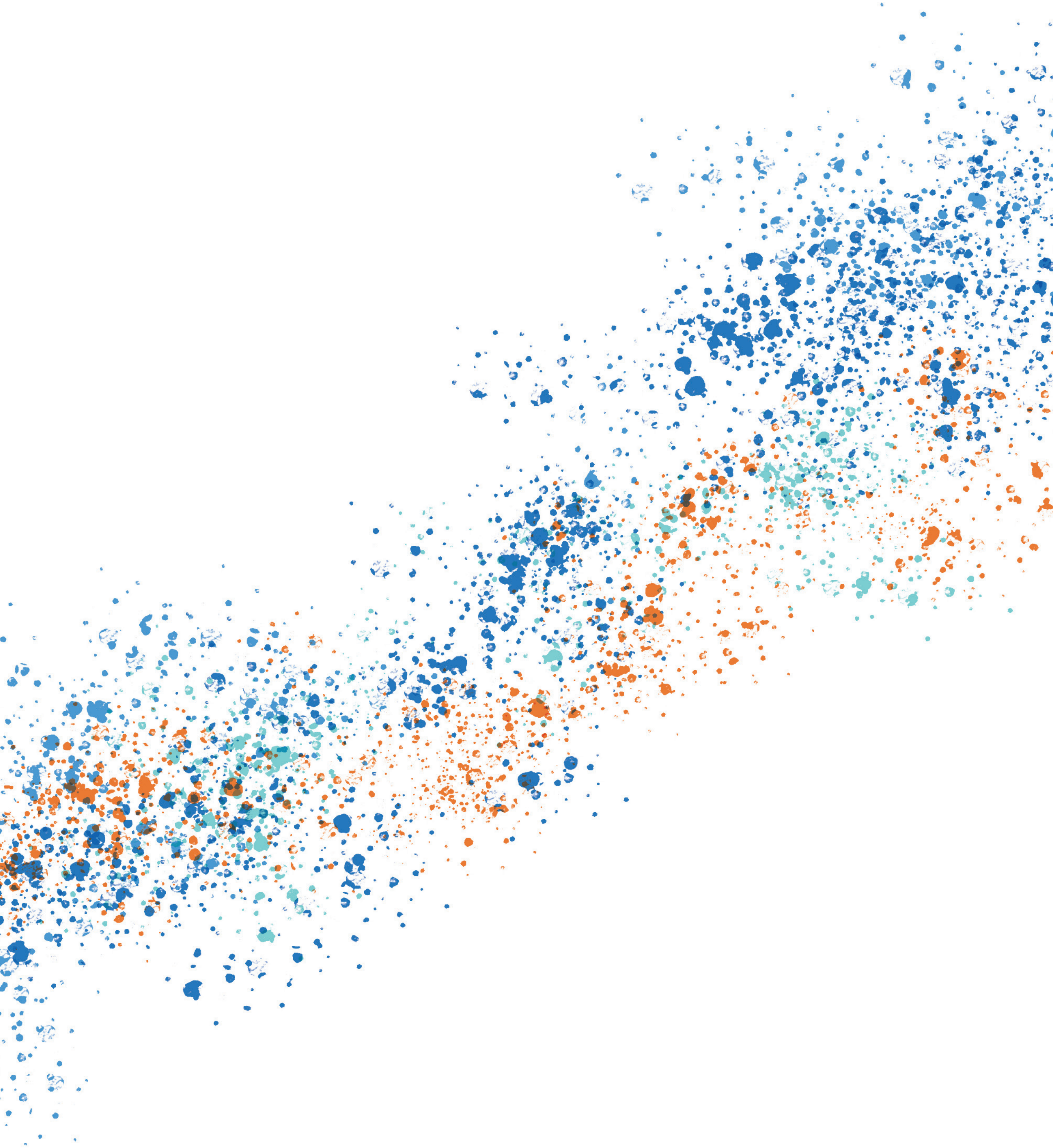
Speaking up	If I don't understand the coach's explanation, I ask the coach about it.
	During practice I ask for help if I need help to improve my swim performance/ swim skills.
	Each practice session I ask the coach what I can do to become a better swimmer.
	Each practice session I discuss with my coach which aspects of my swim performance need improvement.
	If the coach changes an exercise and I don't understand the change, I ask the coach to explain.
	During practice I speak up if I don't understand something or if I don't agree with teammates or the coach.
Effort	I keep working even on difficult tasks.
	I put forth my best effort when performing tasks.
	I concentrate fully when I do a task.
	I don't give up even if the task is hard.
	I work hard on a task even if it is not important.
	I work as hard as possible on all tasks.
	I work hard to do well even if I don't like a task.
	If I'm not really good at a task I can compensate for this by working hard.
	I am willing to do extra work on tasks in order to learn more.
Self-efficacy	I know how to handle unforeseen situations, because I can well think of strategies to cope with things that are new to me.
	I am confident that I could deal efficiently with unexpected events.
	If I am in a bind, I can usally think of something to do.
	I remain calm when facing difficulties, because I know may ways to cope with difficulties.
	I always manage to solve difficult problems if I try hard enough.
	It is easy for me to concentrate on my goals and to accomplish them.
	I can solve most problems if I invest in the necessary effort.
	When I am confronted with a problem, I usually find several solutions.
	No matter what comes my way, I'm usually able to handle it.
	If I persist on a task, I'll eventually succeed.

Note. Evaluation[a]: the ability to assess both the learning process and the result achieved after task execution. Planning[a]: awareness of the demands of a task before it's execution. Reflection[a]: the extent to which respondents are able to appraise what they have learned and to adapt their past knowledge and experiences to improve themselves. Speaking up[b]: taking initiative in searching feedback. Effort[a]: willingness to attain the task goal. Self-efficacy[a]: judgement of one's capability to organize and execute the required action.
[a] Jonker et al. (2010b), [b] Toering et al. (2013)

Appendix B. Cronbach's α and Spearman correlations for self-regulated learning (SRL) subprocesses.

Scale	Chronbach's α	*1*	*2*	*3*	*4*	*5*	*6*
Evaluation	0.84	-	0.67	0.75	0.39	0.44	0.30
Planning	0.75		-	0.67	0.32	0.45	0.30
Reflection	0.89			-	0.38	0.50	0.29
Speaking up	0.75				-	0.21	0.26
Effort	0.82					-	0.45
Self-efficacy	0.84						-

Note. All Spearman correlations are significant ($p < 0.01$).



Chapter 6

Tracking performance and its underlying characteristics in talented swimmers: A longitudinal study during the junior-to-senior transition

Post, A. K., Koning, R. H., Visscher, C., & Elferink-Gemser, M. T. (2023). Tracking performance and its underlying characteristics in talented swimmers: A longitudinal study during the junior-to-senior transition. *Frontiers of Physiology, 14*, https://doi.org/10.3389/fphys.2023.1221567

Abstract

The present study strived to gain a more profound understanding of the distinctions in development between swimmers who are considered to be on track to the senior elite level compared to those who are not. Longitudinal data of 29 talented sprint and middle-distance swimmers (12 males; 17 females) on season best performances (season best times) and underlying performance characteristics (anthropometrics, starts, turns, maximal swimming velocity, stroke index [SI, an indirect measure of swimming efficiency] and lower body power) were collected over four swimming seasons (median of n = 3 seasons per swimmer). Based on their season best performance at early senior age (males aged 18-19; females aged 17-18), some swimmers were considered to be on track to reach the elite level (referred to as high-performing seniors; 6 males and 10 females), whereas others were not (referred to as lower-performing seniors; 6 males and 7 females). Retrospectively studying these swimmers (males and females separately), we found that all high-performing seniors were already on track to the elite level at late junior age (males aged 17; females aged 16), evidenced with faster season best performances throughout their transition compared to their lower-performing peers ($p < 0.05$). Independent sample t-tests revealed that high-performing seniors significantly outscored their lower-performing peers on maximal swimming velocity (males and females), starts and turns (males), SI (females) and lower body power (females) at late junior age ($p < 0.05$). Additionally, multilevel models showed faster rates of development for high-performing seniors on turns and maximal swimming velocity (males), and SI (females) compared to lower-performing peers during the junior-to-senior transition ($p < 0.05$). Particularly, the higher initial levels of swim performance and underlying characteristics at late junior age as well as the ability to keep progressing on season best performances (males and females), turns and maximal swimming velocity (males), and SI (females) during the junior-to-senior transition, may be crucial factors in the attainment of swimming expertise.

Keywords

Youth athletes, talent development, acquisition of expertise, competitive swimming, sports performance, longitudinal analysis, multidimensional approach

Introduction

Competitive swimming is a popular, global sport wherein the finest of margins can determine whether one attains the title or falls short (World Aquatics, 2021). The fastest swimmer is the one who sustains the greatest power output in an efficient and skillful manner throughout the event (Miyashita, 1996). This is influenced by a highly complex interaction of underlying performance characteristics such as anthropometrical (e.g., height), physiological (e.g., muscle power), technical (e.g., stroke index), tactical (e.g., pacing behavior) and psychological (e.g., self-regulation of learning) factors (Barbosa et al., 2010; Saaverda et al., 2010). As a result, swimming performance is not defined by a fixed set of underlying performance characteristics, but rather achieved through individualistic combinations which can change throughout a swimmer's career (Vaeyens et al., 2008; Barbosa et al., 2013; Barbosa et al., 2019; Elferink-Gemser & Visscher 2012).

While acknowledging that swimmers have unique profiles contributing to swimming performance, cross-sectional studies show a range of characteristics that set elite swimmers (i.e., those ranked in the top 50 worldwide) apart from non-elites. These include faster progression of swim performance between and within seasons (Post et al., 2020a; Post et al., 2020b); a highly efficient stroke (Sánchez & Arellano, 2002); pacing behavior which better fits the tasks demands (Menting et al., 2022; Lopez-Belmonte et al., 2022) and advantageous anthropometrics (Rejman et al., 2018). However, with most studies in elite swimming focusing on adults (Costa et al 2012), little is known about the developmental pathway towards swimming expertise. For example, the systematic narrative review of Morais et al. (2021) found only eight longitudinal studies on youth swimmers' development over multiple seasons, highlighting the need for research that shed light on the journey towards swimming excellence.

In particular, research on the development of swim performance and its underlying characteristics during the junior-to-senior transition is lacking. This normative transition signifies the moment at which swimmers start to participate in adult competitions (Larsen & Alfermann et al., 2012), which is typically driven by age-related policies of a swimming federation. Apart from inherent changes in practice and competition, like competing in the open age category instead of annual age categories, the transition from junior to senior in sports frequently aligns with significant other life transitions, such as the move from high school to university (Wylleman and Lavellee, 2004). Consequently, the junior-to-senior transition is considered as the most demanding and difficult phase in the trajectory towards the elite level (Stambulova et al. 2009). During this critical stage, many talented athletes face stagnation, opt for recreational sports, or even discontinue their athletic pursuits, while only a select few master the transition to the senior elite level (Güllich et al., 2023; Stambulova, 2009). In swimming, this is exemplified by the study of Brustio et al., (2021) which found that the junior-to-senior transition rate amongst elite European swimming sprinters was as low as 21% for males and 25% for females. These findings show that most junior elite sprint swimmers were not able to maintain the same level of competitiveness in their senior careers. So far, the specific characteristics that underpin the successful development of swimmers who stay on track towards the senior elite level, as opposed to those who do not, remain unclear.

By following swimmers throughout the junior-to-senior transition and investigating underlying performance characteristics (e.g., anthropometrics, technical skills, muscle power, and maximal swimming velocity) in relation to their performance level at senior age, we may acquire a better understanding about the specific factors that contribute to progression toward elite level swimming performance at this challenging stage. Moreover, insight into the levels and development of underlying performance characteristics during the junior-to-senior transition extends the knowledge about general performance development towards expertise. This may not only enrich the field of sport science but also has the potential to enhance the efficacy and efficiency of athlete development programs by providing science-based reference for coaches and swimmers.

Therefore, the present study strived to gain a more profound understanding of the distinctions in development between swimmers who are considered to be on track to the senior elite level (referred to as high-performing seniors) compared to those who are not (referred to as lower-performing seniors) during the junior-to-senior transition (males aged 16-19 and females aged 15-18). We first examined whether high-performing seniors differed from lower-performing seniors in levels of swim performance and underlying characteristics when they were late juniors (males aged 17; females aged 16). Second, we investigated whether developmental differences in swim performance and underlying performance characteristics emerged during the junior-to-senior transition (males aged 16-19 and females aged 15-18) based on senior performance-level attainment. We hypothesized that high-performing seniors showed better and faster development on both swim performance and its underlying performance characteristics than lower-performing seniors during the junior-to-senior transition.

Materials and Methods

Ethical Approval

All participants were informed of the study's procedures prior to their participation and provided their written informed consent to participate. Informed consent was also obtained from parents of participants who were below 16 years old. All procedures used in the study complied with the Helsinki Declaration and were approved by the research ethics committee of the University Medical Center Groningen, University of Groningen, The Netherlands (202000488).

Participants

Participants were twenty-nine Dutch talented swimmers (12 males, 757 ± 110 World Aquatics Points ; 17 females, 743 ± 82 World Aquatic Points) who progressed through the junior-to-senior transition (males aged 16-19; females aged 15-18). Swimmers were specialized in sprint (50-100m; 8 males and 10 females) or middle-distance (200-400m; 4 males and 7 females) events. According to the age group regulations of the Royal Dutch Swimming Federation (KNZB), swimmers were classified as late juniors (males aged 16-17; females aged 15-16) or early seniors (males aged 18-19; females aged 17-18) based on their calendar age on December 31st of the corresponding season (KNZB, 2022).

During their late junior years, all swimmers participated in one of the (initial) talent development (TD) programs of the KNZB, involving six to ten swim (in-water) training sessions per week. Additionally, they performed mobility training before every morning or afternoon swim session and took part in strength training, typically one to two times per week. Upon reaching early senior age, the group underwent further differentiation. Seventeen swimmers (9 males; 8 females) advanced to the subsequent, higher-level TD programs, while six (1 male and 5 females) swimmers remained in the initial TD program. Additionally, six (2 males and 4 males) swimmers were deselected from the program.

Study design

Longitudinal data on swim performance and underlying performance characteristics were collected over four swimming seasons. Performance data (season best times from all long course swim events) were obtained from Swimrankings (Swimrankings, 2022) at the end of each swimming season. Repeated measures of underlying performance characteristics were conducted as an integral part of all talent development programs, serving as the primary data source for this study.

The frequency of measurement moments varied depending on the specific TD program in which the swimmers were enrolled (see **Figure 1**). This ranged from two to three times a year for the initial TD programs (indicated by the solid red line) to once per month for the subsequent, higher-level TD programs (indicated by the dashed red line). According to coaches' recommendations, the measurement moments were strategically scheduled to align with the competitive calendar for each specific season. The median number of observations was n = 6 in males and n = 10 in females.

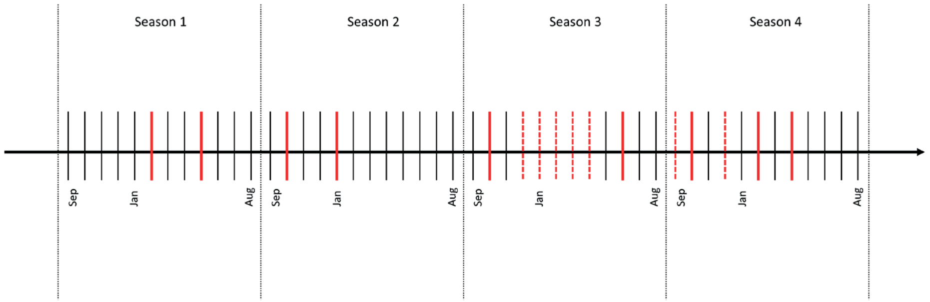


Figure 1. Timeline for data collection over four seasons. All measurement moments included assessment of height, CMJ, start, turn and sprint tests. The solid red line represents the measurement moments for the initial TD programs, while the dashed red line represents the measurement moments for the subsequent, higher-level TD programs.

Measurements

Each measurement moment consisted of land-based tests (height assessment and the countermovement jump test), followed by swimming tests. Additionally, swimmers provided their date of birth and reported their weekly training hours dedicated to strength, mobility and swim training using an online questionnaire (see **Table 1**).

Table 1. Descriptive characteristics of male and female swimmers at late junior age (17 and 16 years respectively) according to their performance level at early senior age.

	Males (N=12)			Females (N=17)		
	High-performing seniors (n=6)	Lower-performing seniors (n=6)	Effect sizes	High-performing seniors (n=10)	Lower-performing seniors (n=7)	Effect sizes
	M ± SD	*M ± SD*	*d*	*M ± SD*	*M ± SD*	*d*
Age (years)	17.6 ± 0.2	17.6 ± 0.2	0.0	16.5 ± 0.3	16.5 ± 0.3	0.0
Swim training (hours per week)	14.7 ± 2.7	16.7 ± 3.0	-0.7	16.0 ± 2.6	15.0 ± 1.1	0.5
Strength training (hours per week)	2.9 ± 1.5	2.2 ± 0.4	0.7	2.0 ± 0.5	2.8 ± 1.0	-1.1
Mobility training (hours per week)	1.7 ± 0.5	1.9 ± 0.4	-0.4	2.3 ± 0.8	2.0 ± 0.8	0.2
Height (cm)	188.1 ± 8.0	185.7 ± 5.7	0.3	177.4 ± 7.2	172.4 ± 3.9	0.8
rLBP (Watt/kg)	41.0 ± 5.7	35.8 ± 10.0	0.6	32.8 ± 3.0 *	28.0 ± 4.8	1.2
rStart (%)	106.1 ± 5.3 *	114.3 ± 5.2	-1.6	109.9 ± 5.0	110.3 ± 6.8	0.0
rTurn (%)	98.3 ± 3.1 **	106.1 ± 2.9	-2.6	100.0 ± 4.3	103.4 ± 3.6	-0.8
rSprint (%)	100.8 ± 2.6 ***	93.0 ± 2.0	3.4	100.8 ± 3.6 *	95.1 ± 3.0	1.7
rSI (%)	82.8 ± 11.5	83.0 ± 7.5	0.0	95.1 ± 6.0 *	79.2 ± 10.0	2.0
rST at late junior age (%)	107.4 ± 2.4 **	114.7 ± 2.9	-2.7	109.1 ± 1.4 *	115.0 ± 3.7	-2.3
rST at early senior age (%)	106.1 ± 1.5 **	111.8 ± 2.0	-3.3	107.9 ± 1.5 *	114.7 ± 4.2	-2.4

Note. 13 freestyle (6 males); 5 butterfly (1 male); 6 breaststroke (3 males); 5 backstroke (2 males) swimmers. Age refers to the calendar age as of December 31st of the corresponding season. rLBP=relative lower body power; rStart= relative start time; rTurn = relative turn time; rSprint = relative maximal swimming velocity; rSI = relative stroke index; rST = relative swim time. * $p < 0.05$ (one-tailed); ** $p < 0.01$ (one-tailed); *** $p < 0.001$ (one-tailed).

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Height

Swimmers' height was assessed using a stadiometer (Seca, 217, Seca GmbH & Co.KG, Germany), which provided a measurement accuracy of 0.1 cm. Measures were taken twice and conducted by the same two researchers. The mean value was documented. A third measure was taken if the difference between the first two exceeded 0.4 cm. The median was then recorded.

Countermovement jump test

Swimmers were instructed to perform three double-leg vertical countermovement jumps (CMJ) without arm swing, which is reported as a valid and reliable test to measure lower body power (Markovic et al., 2004). Lower body power is considered to be of particular importance during starts and turns, as it is in these moments that the lower extremities must generate the greatest impulse to achieve the highest accelerations off the block and wall respectively (Keiner et al., 2021; Jones et al., 2018; West et al., 2011). The jumps began from an upright position, and there was a short break (~2 s) between each trial to allow the swimmers to return to the starting position. Each trial was recorded with a linear position transducer (GymAware PowerTool, GymAware, Australia), which has shown to be a reliable and valid instrument for profiling various variables, including mean power (Cronin et al., 2004). The PowerTool was placed next to the swimmer, clear of their feet. To create an attachment point for the tether, swimmers held a broomstick across their shoulders with their hands. Relative lower body power (rLBP), calculated as the average (concentric) mean power (Watt) over three jumps divided by the swimmer's weight (kilograms), was taken as outcome measure for further analyses.

Swimming tests

Swimming tests consisted of starts, turns and sprints, which swimmers performed in their best stroke with maximal effort, while wearing racing suits. Each test was conducted twice before proceeding to the next. Between efforts, swimmers rested for three till five minutes according to coaches' advice.

Swimming tests were recorded with four underwater digital video camera's (50 Hz, Basler scout, scA1400-30gc, Basler, Germany), positioned on the lateral side of the pool at the 2.5-, 5-, 10-, and 15-m marks, respectively. In addition, the block and flight phase of the start were recorded with a digital video camera above the water, perpendicular to the starting block. Kinematic data of starts, turns and sprints were extracted from these recordings using time video analysis.

Starts

Swimmers were instructed to perform a complete start, including a still position on the block or backstroke ledge, the underwater phase, breakout and subsequent swimming phase. Swimmers were directed to keep swimming until their head reached a distance of 17-m, which was indicated with a marker at the bottom of the pool. This marker ensured that they successfully surpassed the 15-m mark with maximum velocity. Starts were performed with the same material requirements as in major international swimming competitions (starting block with equal dimensions as the Omega OSB11 or the Omega OBL2 PRO backstroke ledge). Start time, defined as time between starting signal (light trigger of the starting device visible in the video footage) until the head of the swimmer passed the 15-m mark, was taken as outcome measure for further analyses (Morais et al., 2019; Born et al., 2022b).

Turns

Swimmers were instructed to perform a complete turn including the underwater phase, break-out and subsequent swimming phase. Swimmers were directed to start their effort at 12.5-m before the wall and to end their effort when their head reached a distance of 17-m, which was indicated with a marker at the bottom of the pool. This marker ensured that they successfully surpassed the 15-m mark with maximum velocity. Turns were performed with the same material requirements as in major international swimming competitions (Omega touch pad on the wall). Turn time, defined as time between 5-m in (head of the swimmer at the 5-m mark before the wall) and 15-m out (head of the swimmer at the 15-mark out of the wall), was taken as outcome measure for further analyses (Morais et al., 2019; Born et al., 2022b).

Mid-pool sprints

Swimmers were instructed to perform a 25-m distance sprint at maximal swimming velocity, starting in the middle of a 50-m pool. Their effort was completed when they touched the wall. Maximal swimming velocity was defined as the clean swimming velocity (10-m distance divided by time for the 10-m distance) between the 10- and 20-m segment of the 25-m trial. Stroke rate (cycles·min-1) was calculated as the number of strokes completed by the swimmer during this 10-m segment (Poujade et al., 2002), one stroke rate cycle being defined as the time between the entry of one hand until the following entry of the same hand (Huot-Marchand et al., 2005). Stroke length (m·cycle-1) was calculated as the ratio between swimming velocity over the 10-m segment and the corresponding stroke rate (Poujade et al., 2002). Stroke index (SI), an indirect measure of swimming efficiency, was calculated by multiplying swimming velocity by stroke length. The SI measures the ability of the swimmer to complete a given distance with a particular speed in the fewest possible number of strokes (m^2·s-1·cycle-1) (Costill et al., 1985). Maximal swimming velocity and SI were taken as outcome measures for further analyses.

Data processing

To enable comparisons among swimmers specialized in different strokes and distances, outcomes were related to meaningful reference values and expressed as a percentage, rather than absolute values (see equation 1). Specifically, swim time was related to the prevailing world record (WR), a method initially introduced by Stoter et al. (2019) in speed skating and subsequently applied in competitive swimming (Post et al., 2020a, 2020b). Lower percentages on relative Swim Time (rST) indicated swim performances closer to the WR.

Furthermore, scores on swimming tests were related to the average start time, turn time, clean swimming velocity and SI of male and female finalists at the European Championships in 2021 (Born et al., 2022b). Stroke-specific data of the 100- and 200-m events were used as reference values for sprinters (50-100-m) and middle-distance (200-400-m) swimmers in our sample respectively (see **Appendix A**). Higher percentages on relative maximal swimming velocity (rSprint) and stroke index (rSI), and lower percentages on relative start- (rStart) and turn time (rTurn), indicate scores more close to the European elite level (set to 100%). For example, the 15-m start time of a junior male freestyle sprinter (6.20s) was related to the average 15-m start time of the 100-m freestyle European male finalists (5.55s), resulting in a relative start time of 111.7% ((6.20/5.55) * 100%).

$$relative\ variable\ x = \frac{absolute\ variable\ x}{reference\ value\ x} \times 100\% \qquad \text{(eq. 1)}$$

Data selection

Rather than considering all observations, we selected the swimmers' season best rST, rStart, rTurn, rSprint along with the corresponding rSI, and rLBP for further analyses (see **Appendix B** for number of measurements by performance level group and age category). Any other data were excluded, minimizing the impact of variations in achievements within a season. The median number of between-season observations was n = 3 in males and females.

Defining Performance Level Groups

A higher- and lower-level performance group were defined according to performance trajectories of international elite swimmers, representing a performance level similar to the top 50 swimmers worldwide of the past 5 years (2017-2022 with the exception of 2020, see Post et al., 2020a). Following the approach adopted in previous studies (Stoter et al., 2019; Post et al., 2020b), the maximum season best rST by age category, sex and swim event of these international elite swimmers was used as performance benchmark (%WR, see **Appendix C**). Swimmers whose season best rST at early senior age (males aged 18-19; females aged 17-18) fell within the corresponding performance benchmark were categorized as high-performing seniors and considered to be on track to reach the elite level (6 males; 10 females). Conversely, swimmers who did not meet the performance benchmark were classified as lower-performing seniors and considered to be off track to reach the elite level (6 males; 7 females). To illustrate, consider a 19-year-old male swimmer competing in the 100m freestyle. If his season best rST is 107.9%, he would be classified in the high-level performance group since it falls within the performance benchmark for 19-year-old males in the 100m freestyle, which is set at 108.9%. However, if his season best rST is 110.0%, he would be classified in the lower-level performance group as it exceeds the corresponding performance benchmark.

Statistics

All data were analyzed for males and females separately, using R (R Core Team, 2019). Data were initially screened on outliers (using box plots), normality (using QQ-plots) and homogeneity of variance (using Levene's test). Outliers (5 in males; 5 in females) were acknowledged as a natural occurrence within the population and, consequently, were not removed from the dataset. Normality was violated in males (strength training, height, rLBP, rStart and rST at early senior age) and females (swim-, strength-, and mobility training, height and rSI). Homogeneity of variance was assumed with the exception of rST at late and early junior age in females.

Cross-tabulation analyses were performed to analyze the relationship between performance level group at early senior (males aged 18-19; females aged 17-18) and late junior age (males aged 17; females aged 16). For high- and lower-performing seniors, mean scores and standard deviations were calculated for swim performance and underlying performance characteristics at the beginning of their junior-to-senior transition (males aged 17; females aged 16). Independent sample t-tests were included to examine between-group differences on age, swim-, strength-, and mobility training (hours per week), height, rLBP, rStart, rTurn, rSprint, rSI, rST at late junior age and rST at early senior age (to ensure correct definition of our performance groups). Mann-Whitney U tests were included to examine between-group differences on variables in which assumptions were violated. For all tests, $p < 0.05$ (one-tailed) was considered statistically significant.

To interpret the scores, effect sizes (Cohen's d values) were calculated. An effect size of approximately 0.20 was considered small, while effect sizes of 0.50, 0.80 and 1.20 were considered medium, large and very large, respectively (Cohen, 1988). A sensitivity power analysis confirmed that our statistical tests were sufficiently sensitive to detect significant differences between performance level groups with a minimum detectable effect size of 1.5 and 1.3 (males and females respectively) (alpha = 0.05, power = 0.80). Statistical tests for measuring invariance were not performed given the nature of our dataset (relatively few observations for many items).

Longitudinal multilevel models were created to describe development of rST, rStart, rTurn, rSprint, rSI and rLBP (dependent variables) as a function of (chronological) age, using the lmer4 package in R (R version 3.6.0). The age effect (which was used as measure for development over time) was not imposed to be identical between high- and lower-performing seniors. Therefore, a nested interaction between age and performance level group at early senior age was included. To represent these two performance level groups in the statistical models, one dummy variable (high-level performance group) was included and the lower-level performance group functioned as reference level. A random intercept model was selected as the most appropriate variance structure, allowing the inclusion of each swimmer's individual trajectory that randomly deviates from the average population trajectory. In sum, the following multilevel model was adopted:

$$Y_{is} = \alpha_i + \beta_1 \times Age_{is} + \beta_2 \times Age_{is} \times High-level\,performance\,group_i + u_i + \varepsilon_{is}$$

$$u_i \sim N\,(0, \sigma_0^2)$$

$$\varepsilon_{is} \sim N(0, \sigma^2) \qquad \text{(eq. 2)}$$

Y_{is} was the dependent variable (e.g., rSprint) for swimming season s of swimmer i, α_i the intercept of swimmer i, Age_{is} the corresponding age value and *High-level performance group*$_i$ the dummy variable indicating whether or not swimmer was in the high-level performance group. The unexplained information was the sum of u_i (between-subject variance) and ε_{is} (residual variance). The models were validated by using visible patterns in residual plots to check violations of homogeneity, normality and independence. Predictor variables were considered significant if the *p* value of the estimated mean coefficient is smaller than 0.05.

Results

Table 1 shows the descriptive statistics, including effect sizes, of male and female swimmers at late junior age (males aged 17; females aged 16) according to their performance level at early senior age. High-performing senior swimmers outscored lower-performing seniors on rST at early senior age ($p < 0.05$; very large effect sizes), confirming a correct definition of performance level groups in both males and females. No significant differences between groups on age and weekly swim-, strength-, and mobility training hours were found ($p > 0.05$).

High-performing senior males scored significantly higher on rSprint ($p < 0.001$), and lower on rStart ($p < 0.05$), rTurn ($p < 0.001$) and rST ($p < 0.01$) at age 17 compared to lower-performing peers. The effect sizes in these four variables were very large. Although not statistically significant, high-performing senior males had higher scores on height (small to medium effect sizes) and rLBP (medium to large effect sizes) at age 17 compared to lower-performing males. Similar scores between groups were found on rSI (no effect).

High-performing senior females scored significantly higher on rLBP ($p < 0.05$), rSprint and rSI ($p < 0.05$), and lower on rST ($p < 0.05$) at age 16 compared to lower-performing peers. The effect sizes in these four variables were very large. Although not statistically significant, high-performing senior females had higher scores on height (medium to large effect sizes) and lower scores on rTurn (large effect sizes) at age 16 compared to lower-performing peers. Similar scores between groups were found on rStart (no effect).

Table 2 shows the cross-tabulation analyses of the relationship between performance level group at early senior and late junior age of male and female swimmers. At early senior age (18-19 years), six of the twelve male swimmers (50%) were classified in the high-level performance group. All six high-performing male seniors (100%) were also categorized as high-performing juniors (16-17 years), whereas four out of the ten (40%) high-performing male juniors switched to the lower-level performance group at early senior age. For females, ten of the seventeen swimmers (59%) were classified in the high-level performance group at early senior age (17-18 years). All ten high-performing female seniors (100%) were also categorized as high-performing juniors (15-16 years), whereas three out of the thirteen high-performing junior females (23%) switched to the lower-level performance group at early senior age.

Table 2. Cross-tabulation analyses of the relationship between performance level group at early senior and late junior age of male and female swimmers.

	Total (N)	High-performing juniors (n)	Lower-performing juniors (n)
Males	12 (100%)	10 (83%)	2 (17%)
High-performing seniors	6 (50%)	6 (100%)	0 (0%)
Lower-performing seniors	6 (50%)	4 (67%)	2 (33%)
Females	17 (100%)	13 (76%)	4 (24%)
High-performing seniors	10 (59%)	10 (100%)	0 (0%)
Lower-performing seniors	7 (41%)	3 (43%)	4 (57%)

Note. Swimmers whose relative season best performaces at late junior age (males 16-17 years, females 15-16 years) fell within the performance benchmark) were categorized as high-performing juniors. Conversely, those swimmers who were not fast enough were classified as lower-performing juniors.

Developmental models according to performance level group at early senior age

Table 3 shows the developmental models on rST, rStart, rTurn, rSprint, rSI and rLBP created for males and females. Each model consists of two age effects, which allows for different rates of development between high- and lower-performing seniors. The "age" term denotes the development of lower-performing seniors, whereas "age + age × high-level performance group" denotes the development of high-performing seniors. To illustrate (using the fixed effects of the model only), the rST for a high-performing senior male at age 17 will be predicted as follows:

$$rST = 128.09 + (-0.79 \times 17) + (-0.34 \times 17) = 108.88 \qquad \text{(eq. 3)}$$

Given the study's primary focus on differences between high- and lower-performing swimmers, particular emphasis will be placed on analyzing the interaction term (age × high-level performance group). A significant interaction term would indicate a faster rate of development of high-performing swimmers compared to their lower-performing peers.

In males, high-performing senior swimmers showed significant faster progression over time on rST ($p < 0.001$), rTurn ($p < 0.01$) and rSprint ($p < 0.001$) compared to lower-performing senior swimmers. In females, high-performing senior swimmers showed significant faster progression over time on rST ($p < 0.01$) and rSI ($p < 0.01$). No significant developmental differences between groups were found on rStart and rLBP (males and females), rSI (males only) and rTurn and rSprint (females) ($p > 0.05$). **Figure 2** (males) and **Figure 3** (females) reflect the predicted development of high- and lower-performing seniors during the junior-to-senior transition.

Table 3. Model estimates for male (N=10 with 28 observations) and female (N=14 with 39 observations) swimmers.

	rST		rStart		rTurn		rSprint		rSI		rLBP	
	Estimates (S.E.)	*p value*	*Estimates (S.E.)*	*p value*	*Estimates (S.E.)*	*p value*	*Estimates (S.E.)*	*p value*	*Estimates (S.E.)*	*p value*	*Estimates (S.E.)*	*p value*
Males												
Fixed effects												
Intercept	128.09 (4.41)	**<0.001**	142.88 (7.59)	**<0.001**	118.59 (8.94)	**<0.001**	94.76 (5.81)	**<0.001**	73.08 (17.49)	**0.001**	-9.57 (22.66)	0.340
Age	-0.79 (0.24)	**0.002**	-1.70 (0.42)	**<0.001**	-0.72 (0.49)	0.082	-0.12 (0.32)	0.359	0.71 (0.96)	0.236	2.62 (1.26)	**0.030**
Age × high-level performance group	-0.34 (0.09)	**<0.001**	-0.31 (0.18)	0.051	-0.35 (0.11)	**0.002**	0.45 (0.08)	**<0.001**	-0.13 (0.25)	0.304	0.19 (0.24)	0.222
Random Effects												
σ^2	0.85		2.64		4.46		1.79		16.11		18.29	
τ_{00}	6.48		25.97		7.74		4.26		45.54		40.24	
Marginal R^2 / Conditional R^2	0.61 / 0.95		0.31 / 0.94		0.50 / 0.82		0.74 / 0.92		0.02 / 0.74		0.16 / 0.74	
Females												
Fixed effects												
Intercept	112.95 (3.34)	**<0.001**	135.38 (6.14)	**<0.001**	116.76 (6.66)	**<0.001**	97.00 (8.22)	**<0.001**	81.94 (12.61)	**<0.001**	-6.40 (13.12)	0.316
Age	-0.02 (0.20)	0.454	-1.78 (0.38)	**<0.001**	-0.97 (0.41)	**0.012**	0.03 (0.49)	0.479	-0.06 (0.76)	0.467	2.44 (0.78)	**0.003**
Age × high-level performance group	-0.21 (0.06)	**0.001**	0.26 (0.17)	0.075	0.01 (0.15)	0.482	0.20 (0.12)	0.059	0.76 (0.23)	**0.002**	-0.22 (0.16)	0.089
Random Effects												
σ^2	0.87		2.77		3.59		6.36		14.32		11.89	
τ_{00}	2.71		24.25		16.10		10.01		40.19		14.86	
Marginal R^2 / Conditional R^2	0.43 / 0.86		0.15 / 0.91		0.05 / 0.83		0.13 / 0.66		0.38 / 0.84		0.22 / 0.65	

Note. “Age” term denotes development of lower-performing seniors. “Age + Age × high-level performance group” denotes development of high-performing seniors.
Abbreviations: rST (relative swim time); rStart (relative start time); rTurn (relative turn time); rSprint (relative maximal sprint velocity); rSI (relative stroke index); rLBP (relative lower body power).
Significant predictor variables ($p < 0.05$) are denoted in bold with adjustments made for one-sided hypothesis testing in the calculation of the p value.

6

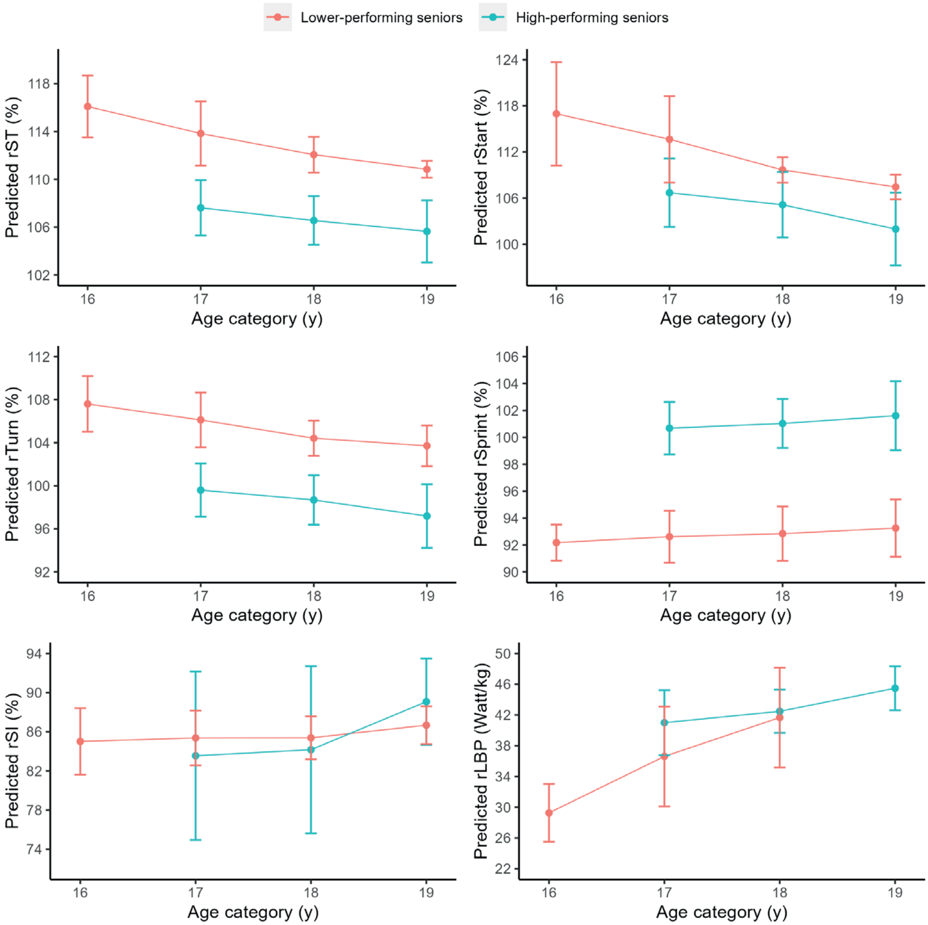

Figure 2. Predicted development as function of age (mean ± SD) of swim performance and underlying performance characteristics in males (N=10 with 28 observations).

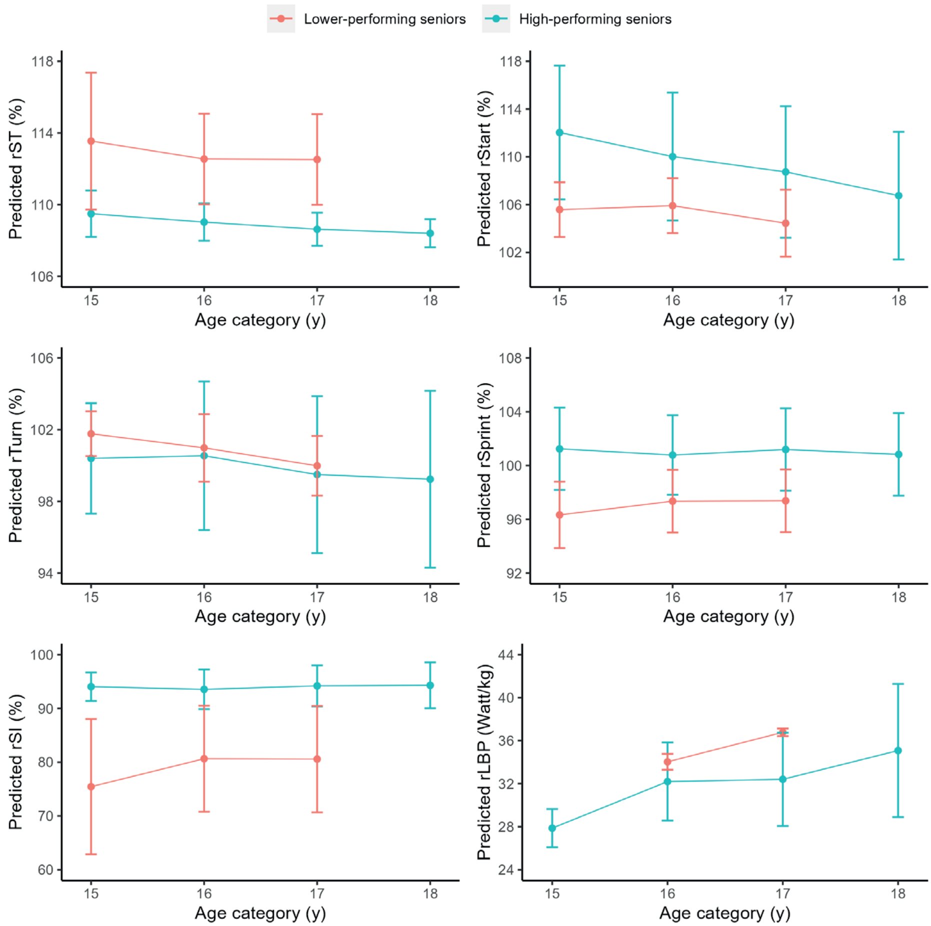

Figure 3. Predicted development as function of age (mean ± SD) of swim performance and underlying performance characteristics in females (N=14 with 39 observations).

6

Discussion

The present study strived to gain a more profound understanding of the distinctions in development between swimmers who are considered to be on track to the senior elite level (referred to as high-performing seniors; 6 males and 10 females) compared to those who are not (referred to as lower-performing seniors; 6 males and 7 females). Retrospectively studying these swimmers, we found that high-performing seniors (males aged 18-19 and females aged 17-18) outperformed their lower-performing peers on most of the assessed underlying characteristics at late junior age (males aged 17; females aged 16). Furthermore, high-performing seniors were characterized with significantly faster development in season best performances (for both males and females), maximal swimming velocity and turns (males), and SI (females) during the junior-to-senior transition (males aged 16-19; females aged 15-18).

Performance

Our findings showed that high-performing seniors were already on track to the elite level at age 17 (males) and age 16 (females). At this particular age, it became evident that these swimmers demonstrated significantly faster season best performances compared to their lower-performing peers (very large effect sizes), which aligns with previous research of Post et al. (2020a). Moreover, we found that high-performing seniors showed significantly faster development of swim performance during the junior-to-senior transition. This further amplified their initial advantages over lower-performing peers.

While all high-performing seniors were classified as high-performing juniors, it is important to note that none of the lower-performing juniors transitioned to the high-performing senior group. This observation indicates that bridging the performance level gap faced by lower-performing juniors is exceptionally challenging. Moreover, it suggests that the development of swim performance becomes more stable during the late junior years (males aged 16-17; females aged 15-16), which is in line with previous work of Costa et al. (2011). As such, we state that the importance of performance level increases as swimmers approach their age of peak performance (Allen & Hopkins, 2015), and that a high level of swim performance at late junior age (i.e., being on track), may be required to advance to the senior elite level, which was also observed in other individual sports like cycling (Mostaert et al., 2022; Gallo et al., 2022). Additionally, we have found that not all high-performing juniors ended up as high-performing seniors. This observation highlights that being on track at late junior age does not guarantee the successful continuation to the senior elite level, which aligns with previous studies (Brustio et al., 2021; Barreiros et al., 2014). Furthermore, it underscores the difficulty of sustaining an upward trajectory towards swimming expertise, thereby counteracting the commonly observed plateau in progress that tends to occur during the junior-to-senior transition (Born et al., 2022a).

Underlying performance characteristics and its development

A closer analysis of the assessed underlying characteristics of swim performance revealed that high-performing seniors were taller (small effect sizes in males; large effect sizes in females) and significantly outperformed lower-performing peers in terms of maximal swimming velocity (very large effect sizes) at late junior age (males aged 17; females aged 16). These findings align with previous studies that have reported advantageous anthropometrics and higher swimming speed among faster swimmers, particularly in the youth category (Morais et al 2017; Barbosa et al., 2019; Morais et al., 2022). It is noteworthy that both male and female high-performing seniors exhibit swimming speeds at late junior age that are nearly comparable to those of finalists of the European Championships in 2021, as evidenced by the values approaching 100%. Additionally, high-performing senior females demonstrated significantly higher SI at late junior age compared to their lower-performing peers (very large effect sizes). This finding corresponds with existing literature showing that faster (early junior) swimmers distinguished themselves from others with better SI (Morais et al., 2021; Barbosa et al., 2019). However, contrary to our initial hypothesis, no differences in SI were observed among males. Given that their SI scores are the farthest from reaching values close to 100%, overall swimming efficiency seems to be the (relatively) weakest point for males when compared to other variables at late junior age.

It is important to note that both maximal swimming velocity and SI were derived from the 25-meter sprint test, and therefore, they should be considered together. When considering these variables collectively, it can be concluded that high-performing seniors demonstrated higher maximal swimming velocity with the same (males) or even higher levels of SI (females) at late junior age compared to their peers. This may be an important advantage as swimmers need to maintain optimal power output in an efficient and skillful manner throughout the event (Miyashita, 1996). Moreover, we found that high-performing seniors demonstrated significantly faster rates of progression on maximal swimming velocity (males) and SI (females) during the junior-to-senior transition. Notably, it is precisely in these variables that lower-performing peers experienced a plateau in their progress (as evidenced by beta values close to zero), indicating that high-performing seniors were extending their advantages even further over time.

As expected, high-performing seniors demonstrated higher lower body power (medium effect sizes in males; very large effect sizes and significant in females) and faster turns (very large effect size and significant in males; large effect sizes in females) compared to lower-performing seniors at late junior age. In the case of turns, high-performing males demonstrated significantly faster rates of progression. Moreover, starts were significantly faster for high-performing senior males (very large effect sizes) at late junior age, whereas no differences were observed among females. When compared to other variables, it is evident that females' starts are their relatively weakest point, as their start performances show the greatest deviation from values close to 100%. It is worth noting, however, that our study assessed the total start and turn times and did not explore specifically the various components involved, such as the block/push-off phase, underwater phase or clean swimming phase. By conducting more detailed investigations of these components in future studies, we could attain a more comprehensive understanding of the specific phases in which differences in starts and turns emerge. Moreover, the inclusion of measures related hydrodynamics, power output in the water and aerobic capacity could offer insights into the mechanisms behind the observed distinctions between high- and lower-performing swimmers in the present study.

Training

Our findings are inherently connected to both the quantity and quality of swim training. As such, inter-individual variations in training characteristics could help explain our results. Our study suggested that high-performing senior females tend to be involved in more weekly swim training hours compared to their lower-performing peers at age 16 (medium to large effect sizes). This suggests that high-performing females spent more time in the water to work on their skills, which may have benefitted their progression (Baker & Young, 2014). It is important to note, however, that the increase in swim training hours does not automatically translate to higher performance levels, which is evidenced by high-performing senior males who appear to have participated in fewer weekly swim training hours compared to their lower-performing peers at age 17 (medium to large effect sizes). This could indicate that high-performing males derived more from their training sessions in terms of quality.

The quality of training encompasses factors such as self-regulation of learning (SRL). SRL indicates the extend to which individuals are metacognitively, motivationally and behaviorally proactive in their own learning processes (Zimmerman, 1986; 2006). Previous research on SRL in swimming showed that youth swimmers on track to the elite level are characterized by more frequent use of reflection processes during training and evaluation processes after training, which suggest that they learn and train in a more efficient and effective manner (Post et al., 2022). Ultimately, this could contribute to a higher quality of daily training, which may result in greater improvements during a season and higher performance levels. As talented swimmers approach the senior elite level, the difficulty of making progress increases significantly (Born et al., 2022a), partly due to the principle of diminishing returns of training (Hoffman, 2014). Hence, SRL processes may become of particular importance during the junior-to-senior transition.

Moreover, a swimmer's coach plays an essential role in the quality of training. Depending on the coach's vision of swimmers' performance development, specific aspects of swimming performance (such as starts, turns, or technique) are emphasized in the training program (Marinho et al., 2020). Combined with a swimmer's training history, fitness level, and specialization, a personalized training approach is designed, including strength-, and mobility training. Therefore, future studies investigating the inter-individual differences in these training characteristics and their relation to the development of swim performance and underlying factors would be of great value in advancing our understanding of the pathway to swimming expertise.

Strengths and weaknesses

The uniqueness of the present study lies in its integration of study design, sample, and analysis, which sets it apart from other studies in multiple ways. First of all, our longitudinal analysis of performance and multiple underlying performance characteristics (multi-dimensional approach) allows for a more comprehensive understanding of the complex nature of athlete development, resulting in a more nuanced and insightful analysis of progression towards elite level swimming performances. Second and unlike previous studies, we followed top-tier national age group swimmers during their junior-to-senior transition. We particularly focused on the late junior and the early senior years, a time span of four years at the end of the talent trajectory (males aged 16-19; females aged 15-18). It is worth noting that this specific group of swimmers has been underrepresented in existing research, with an even greater lack of focus on female athletes. As such, the present study shed a light on the unique developmental characteristics of talented male and female swimmers, revealing both similarities and differences between sexes. This underscores the importance of recognizing that findings from male swimmers cannot be directly extrapolated to females, emphasizing the need for sex-specific considerations and individualized approaches. Third, our analysis focused on differences between high-performing and lower-performing senior swimmers in relation to international reference values, while considering different rates of development between these performance level groups in our models. Opposite to their lower-performing peers, high-performing seniors are considered to be on track to the senior elite level. This group division was defined by benchmarks derived from the observed developmental pathway of international elite swimmers who ranked among the top 50 worldwide. Moreover, scores on swimming tests were related to (in-competition) levels of starts, turns, maximal swimming velocity and SI achieved by finalists of the European Championships in 2021. This comparison enabled us to assess the level of late-junior swimmers in relation to the level they need to attain as senior elite swimmers. Taken together, the present study is the first to provide evidence for differences in developmental pathways (both on performance and its underlying characteristics) of both male and female senior swimmers who are on track to the elite level compared to those who are not during the junior-to-senior transition.

Alongside the strengths, it is important to acknowledge and address the limitations that exist within the present study. Unsurprisingly, we faced the challenge of a relatively small sample sizes, which is inherent in elite sports research (Skorski & Heckseden, 2021). As a result, the statistical power of our analysis was constrained, limiting our ability to detect anything other than substantial differences between groups. This limitation increases the likelihood of interpreting minor changes in variables as having no effect, emphasizing the need for cautious interpretation of the study's findings. However, it is essential to recognize that even subtle changes can hold practical significance, particularly in the context of elite sports (Gabbett et al., 2017). Therefore, to ensure a comprehensive interpretation of our results, we placed particular emphasis on effect sizes. Effect sizes provide a measure of the magnitude of the observed effects (Nuzzo, 2014), allowing us to evaluate the practical significance of even the smallest changes. Additionally, we implemented a data pooling strategy to increase our sample size by combining the data from all our swimmers. However, due to this approach, we were unable to include stroke-specific analyses and stroke-specific variables, such as stroke rate, in the present study.

Furthermore, it is worth emphasizing that not all swimmers in our study sustained their involvement in TD programs throughout the junior-to-senior transition. Therefore, we cannot rule out a survivorship bias given that our measurements of underlying performance characteristics were exclusively conducted among swimmers who remained in these programs. Consequently, the outcomes of our study specifically pertain to swimmers who remained in the system, reflecting the coach’s belief that a swimmer has the potential to make it to the senior elite level. It is recommended that future studies attempt to account for all swimmers initially involved in these kinds of measurements; however, this is challenging as swimmers who are deselected from talent development programs may not continue their efforts in the same way or may choose to pursue alternative career paths and retire (known as self-selection; Biele et al., 2019). Finally, the COVID-19 pandemic occurred during the study period and may have introduced potential confounding factors, such as periods of detraining, which could have influenced our findings (Zacca et al., 2019; Ruiz-Navarro et al., 2022). These factors must be considered when interpreting the findings of our study and in applying them to broader contexts of talent development in swimming (Elferink-Gemser & Visscher 2012).

Perspective

The present study advances our understanding of progression towards elite level swimming performance in sprint and middle-distance events. Specifically, it underscores the significance of high initial levels of swim performance and underlying characteristics at late junior age (within 10% of international elite reference values, except for SI in males) as well as the ability to keep progressing on season best performances, maximal swimming velocity and turns (males) and SI (females) during the junior-to-senior transition. These may be crucial factors in the attainment of swimming expertise. Coaches and swimmers could focus on developing these underlying characteristics while being mindful of the differences in developmental profiles between males and females and tailor their training programs accordingly. Moreover, the study’s insights into the scores and developmental patterns of high-performing seniors could support coaches in monitoring their swimmers' progression towards the elite level. However, coaches should consider these findings as a starting point rather than an endpoint for further development, as performance levels are influenced by unique combinations of underlying characteristics in which relative weaknesses can be compensated with strengths. Furthermore, it is important for coaches to be aware that for swimmers who are close to achieving 100% scores on swimming tests, ongoing development is crucial. This development is necessary to effectively bridge the gap between performance in isolated tests and performance in actual competitions. As our findings show that differences between high- and lower-performing seniors manifest at least at late junior age (males aged 17; females aged 16), it would be interesting to further investigate the earlier stages of their junior years. This could help elucidate when these differences first emerge as well as the factors that facilitate or hinder swimmers' performance and progression, such as biological and environmental variables (e.g.,, maturation, training and selection procedures).

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Appendices

Appendix A. References values of key performance indicators of European male and female finalists (retrieved from Born et al 2022).

	Clean swimming speed (m/s)	Stroke index	Start time (s)	Turn time (s)
Males (100-m events)				
Backstroke	1.77	3.81	6.20	10.15
Breaststroke	1.60	2.80	6.43	11.77
Butterfly	1.84	3.64	5.53	10.39
Freestyle	1.98	4.63	5.55	9.51
Males (200-m events)				
Backstroke	1.62	3.81	6.46	10.99
Breaststroke	1.48	3.71	6.47	12.55
Butterfly	1.68	3.41	5.91	11.55
Freestyle	1.81	4.54	5.84	10.39
Females (100-m events)				
Backstroke	1.58	3.11	7.09	11.48
Breaststroke	1.43	2.56	7.55	13.37
Butterfly	1.63	2.84	6.33	11.63
Freestyle	1.77	3.84	6.25	10.62
Females (200-m events)				
Backstroke	1.48	3.23	7.61	12.43
Breaststroke	1.34	3.04	7.83	14.05
Butterfly	1.50	2.63	6.96	12.88
Freestyle	1.64	3.69	6.65	11.51

Appendix B. Number of swimmers measured in one through four seasons and number of season best observations per age category during the junior-to-senior transition.

	N swimmers	n swimmers measured for 1 season	n swimmers measured for 2 seasons	n swimmers measured for 3 seasons	n swimmers measured for 4 seasons	N obs.	n obs. (at age 15)	n obs. (at age 16)	n obs. (at age 17)	n obs. (at age 18)	n obs. (at age 19)
Males											
High-performing seniors	6	1	2	3	0	14	-	0	6	5	3
Lower-performing seniors	6	1	1	3	1	16	-	3	6	4	3
Females											
High-performing seniors	10	0	1	9	0	29	4	10	9	6	-
Lower-performing seniors	7	3	2	2	0	13	2	7	4	0	-
Total	29	5	6	17	1	72	6	20	25	15	6

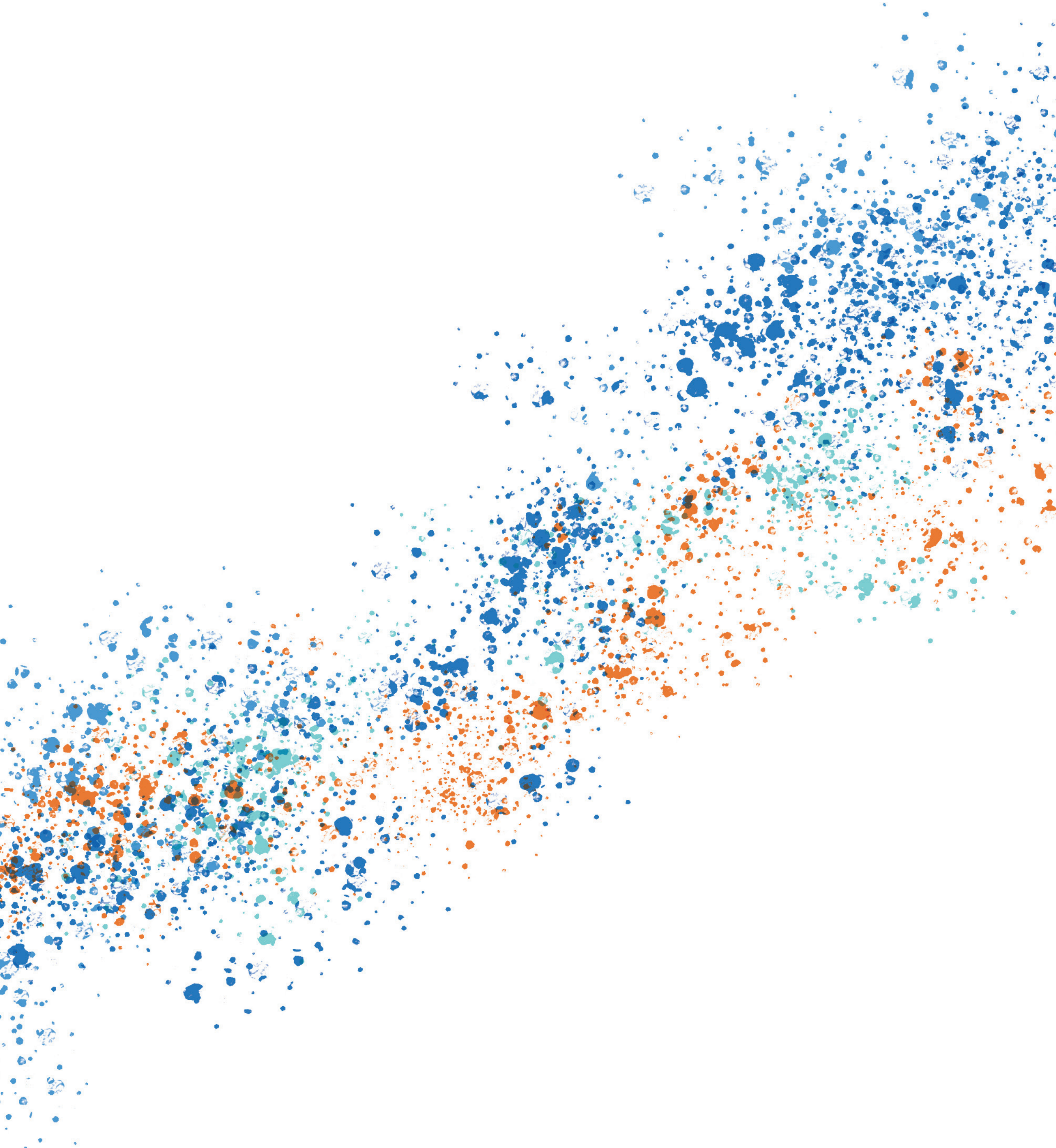
Note. N swimmers = total number of unique swimmers participating in the study; n swimmers = number of swimmers measured in one through four seasons; N obs. = total number of season best observations; n obs. = number of season best observations per age category.

Appendix C. Performance benchmarks (%WR) by age category, sex and swim event derived from international elite swimmers.

	Event	Age category	Performance benchmark (%WR)
Males	50 Backstroke	18	111.8
	100 Backstroke	18	111.4
	200 Backstroke	18	111.0
	50 Breaststroke	18	113.0
	100 Breaststroke	18	111.5
	200 Breaststroke	18	111.8
	50 Butterfly	18	113.8
	100 Butterfly	18	111.0
	200 Butterfly	18	111.4
	50 Freestyle	18	112.9
	100 Freestyle	18	112.1
	200 Freestyle	18	111.3
	400 Freestyle	18	110.1
	200 Medley	18	111.6
	400 Medley	18	111.0
	50 Backstroke	19	111.5
	100 Backstroke	19	109.0
	200 Backstroke	19	109.5
	50 Breaststroke	19	113.0
	100 Breaststroke	19	110.9
	200 Breaststroke	19	109.4
	50 Butterfly	19	112.2
	100 Butterfly	19	109.8
	200 Butterfly	19	109.8
	50 Freestyle	19	112.7
	100 Freestyle	19	108.9
	200 Freestyle	19	110.1
	400 Freestyle	19	107.8
	200 Medley	19	110.1
	400 Medley	19	109.8
Females	50 Backstroke	17	111.5
	100 Backstroke	17	112.1
	200 Backstroke	17	112.8
	50 Breaststroke	17	114.7
	100 Breaststroke	17	113.2
	200 Breaststroke	17	114.5
	50 Butterfly	17	116.7
	100 Butterfly	17	115.0

6

Event	Age category	Performance benchmark (%WR)
200 Butterfly	17	111.6
50 Freestyle	17	114.9
100 Freestyle	17	110.9
200 Freestyle	17	109.4
400 Freestyle	17	110.8
200 Medley	17	112.0
400 Medley	17	111.8
50 Backstroke	18	111.3
100 Backstroke	18	111.1
200 Backstroke	18	110.9
50 Breaststroke	18	114.3
100 Breaststroke	18	112.8
200 Breaststroke	18	114.0
50 Butterfly	18	117.4
100 Butterfly	18	113.7
200 Butterfly	18	111.2
50 Freestyle	18	113.9
100 Freestyle	18	111.1
200 Freestyle	18	109.1
400 Freestyle	18	109.6
200 Medley	18	110.8
400 Medley	18	110.9



Chapter 7

Growing up and reaching for the top: A longitudinal study on swim performance and its underlying characteristics in talented swimmers

Post, A. K., Koning, R. H., Visscher, C., & Elferink-Gemser, M. T. (2024). Growing up and reaching for the top: A longitudinal study on swim performance and its underlying characteristics in talented swimmers. *Journal of Sport Sciences, 42*(2), 132-145, Advance online publication. https://doi.org/10.1080/02640414.2024.2322253

Abstract

The present study strived to gain a more profound understanding of the distinctions in development between swimmers who are considered to be on track to the elite level at late junior age (males aged 16; females aged 15) compared to those who are not. In this effort, swimmers were followed during their pubertal years (males aged 13-15; females aged 12-14). which marks a period when performance development aligns with maturation. Longitudinal data of 90 talented sprint and middle-distance swimmers on season best times (SBT) and underlying performance characteristics (anthropometrics, maximal swimming velocity, stroke index [SI] and countermovement jump [CMJ]) were collected over three swimming seasons. Based on their SBT at late junior age (males aged 16; females aged 15), swimmers were classified as high-performing late juniors or lower-performing late juniors. Retrospectively studying these swimmers, we found that all but two high-performing late juniors were already on track to the elite level at early junior age (males aged 13; females aged 12), evidenced with faster SBT throughout puberty compared to their lower-performing peers (p <0.05). Independent sample t-tests revealed that high-performing late juniors significantly outscored their lower-performing peers when they were early juniors on maximal swimming velocity (males aged 13-15 and females aged 12-14), SI (males aged 13 and 14; females aged 12), CMJ (females aged 14) and height (females aged 13 and 14, p <0.05) Additionally, multilevel models showed faster rates of development for high-performing late juniors on maximal swimming velocity (males and females) and SI (males) compared to lower-performing peers throughout puberty (p <0.05). Higher initial levels of SBT and underlying performance characteristics at early junior age as well as the faster rates of development on SBT, maximal swimming velocity and SI (males only) during the pubertal years, may be crucial factors in maintaining the trajectory towards the elite level after puberty.

Keywords

Growth and maturation, talent development, acquisition of expertise, competitive swimming, longitudinal analysis

Introduction

Competitive swimming is a sport where every fraction of a second can make the difference between winning or losing (World Aquatics, 2016). This compels elite swimmers to pursue the perfect race, constantly refining even the smallest details of their performances (ANP, 2017). However, these swimmers did not start out as world-class athletes; they were once aspiring junior swimmers who belonged to a group where only a tiny minority would eventually reach the top (Brustio et al., 2021; Güllich et al., 2023; Barreiros et al., 2014). What characterizes their successful development towards swimming expertise compared to their peers who did not make it to the top?

Undoubtedly, a significant element in the progression from competing at local junior meets to excelling at the World Championships is the continuous improvement of swim performance over time. This increase could be attributed to the development of swimmers' underlying performance characteristics, including anthropometric, physiological, technical, tactical, and psychological factors (Elferink-Gemser & Visscher, 2012). Accordingly, researchers emphasize the importance of conducting multi-dimensional and longitudinal studies to unravel the pathway towards swimming expertise (Cobley and Till, 2017). Yet, such studies are scarce in the literature, leaving a significant gap for further exploration (Morais et al., 2021).

A particularly intriguing period to investigate would be the pubertal years, which marks a period when performance development aligns with maturation (Malina et al., 2004a). Maturation reflects the timing and tempo of progress towards the mature adult state, which highly varies between individuals (Malina et al., 2004a). It is the driving force for many processes, including the adolescent growth spurt, which typically occurs at 12 ± 2 years in girls and 14 ± 2 years in boys (Till et al., 2020). Previous studies have shown a strong relationship between maturation and physical performance indicators such as size, strength, power and speed (Malina et al., 2004b; Abbott et al., 2021a; Lätt et al., 2009; Oliveira et al., 2021). Moreover, Morais et al. (2014, 2022) found that swimmers minimize performance impairment or even progress in periods of detraining due to growth spurts.

Commonly, the pubertal years also signify the time when the initial stages of talent identification processes are carried out (KNZB, 2023). However, due to the potential asynchrony between chronological and biological age (Towlson et al., 2018), accurately assessing a swimmer's current performance level can be challenging during this key developmental phase (Malina et al., 2004a). Furthermore, given that maturing swimmers undergo natural, yet highly individual and unpredictable improvements in performance, it can be difficult to distinguish between progress resulting from growing up and progress indicative of the potential for future elite level performances (Malina et al., 2004a). These challenges can create confusion in evaluating a swimmer's potential and may introduce maturity-related biases that favor early-maturing swimmers and overlook those who mature later in talent selection processes (Malina et al., 2015).

Hence, gaining insight into the development of performance and its underlying performance characteristics (e.g., height, maximal swimming velocity, stroke index and CMJ) throughout puberty, while differentiating between performance levels, is essential to optimize talent identification and development (TID) in swimming. Obtaining a thorough understanding of the developmental pathways during the pubertal years, such as objective insights into skill levels and rates of progression for swimmers who are on track to the elite level in comparison to those who are not, can provide valuable knowledge to contextualize a swimmer's current performance and future potential. This can facilitate the advancement of science-based, informed decision-making processes, which may lead to more effective and improved strategies in TID.

Therefore, the present study followed swimmers throughout puberty (males aged 12-15; females aged 11-14) and retrospectively analyzed their developmental patterns, differentiating by their performance level at the end of puberty (males aged 16; females aged 15). We first examined whether swimmers who are considered to be on track to the elite senior level (referred to as high-performing late juniors) differed from those who are not (referred to as lower-performing late juniors) on levels of swim performance and underlying performance characteristics throughout puberty. Second, we investigated whether developmental differences in swim performance and underlying performance characteristics emerged during the pubertal years based on late junior performance-level attainment. We hypothesized that high-performing late junior swimmers showed better scores and faster rates of development on both swim performance and its underlying performance characteristics than lower-performing late junior swimmers throughout puberty.

Methods

Ethical Approval

All participants were informed of the study's procedures prior to their participation and provided their written informed consent to participate. Informed consent was also obtained from parents of participants who were below 16 years old. All procedures used in the study complied with the Helsinki Declaration and were approved by the local research ethics committee.

Participants

Participants were ninety Dutch talented swimmers (47 males, 14.6±1.0 years; 43 females, 13.2±1.1 years) who were followed throughout the junior years of their swimming career (males aged 12-15; females aged 11-14). All swimmers participated in the National Dutch Junior Championships ("Nederlandse Jeugd & Junioren Kampioenschappen"), and were classified as national-level athletes, corresponding to Tier 3 in the classification system proposed by McKay et al. (2022). Swimmers were specialized in sprint (50-100-m; 32 males and 35 females) or middle-distance (200-400-m; 15 males and 8 females) events. According to the age group regulations of the Royal Dutch Swimming Federation (KNZB), swimmers were classified as early junior (males aged 12-13 years; females aged 11-12 years), mid junior (males aged 14-15 years; females aged 13-14 years) and late junior swimmers (males aged 16-17 years; females aged 15-16 years) based on their calendar age on December 31st of the corresponding season (KNZB, 2022). Swimmers' average performance level at late junior age corresponded to 597 ± 106 World Aquatics Points for males and 571 ± 86 World Aquatic Points for females.

Study design

Longitudinal data on swim performance and underlying performance characteristics were collected over three swimming seasons. Performance data (season best times from all long course swim events) were obtained from Swimrankings (Swimrankings, 2022) at the end of each swimming season. Repeated measures of underlying performance characteristics were conducted during four measurement moments during the National Dutch Junior Championships (see **Figure** 1). For males and females, the median number of measurements was n = 3, taken over a period spanning from 6 to 18 months.

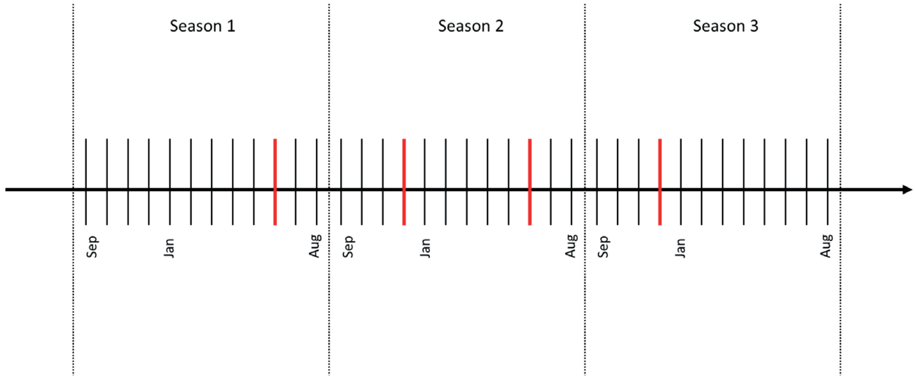


Figure 1. Timeline for data collection over three seasons. All measurement moments included assessment of height, sitting height, weight, CMJ, and mid-pool sprint tests.

Testing battery

Each measurement moment consisted of land-based tests (anthropometric assessment and the countermovement jump test), followed by a swimming test. Additionally, swimmers provided their date of birth and reported their weekly training hours dedicated to swim (in-water) training using an online questionnaire (see **Table 1**).

Table 1. Descriptive characteristics of male and female swimmers according to their age category and performance level group at late junior age.

		Males (N=47)			Females (N=43)		
		High-performing late juniors	Lower-performing late juniors	Effect sizes	High-performing late juniors	Lower-performing late juniors	Effect sizes
		M ± *SD*	*M* ± *SD*	*d*	*M* ± *SD*	*M* ± *SD*	*d*
All	Age of peak height velocity (APHV)	13.1 ± 0.4	13.2 ± 0.5	-0.3	11.5 ± 0.3 *	11.7 ± 0.3	-0.9
	rST at late junior age (%)	112.0 ± 2.3 ***	123.6 ± 6.4	-2.3	114.1 ± 1.9 ***	123.3 ± 6.1	-1.7
12 years	Age (years)	-	-	-	12.4 ± 0.3	12.5 ± 0.3	-0.2
	Swim training (hours per week)	-	-	-	7.8 ± 1.4	6.9 ± 2.2	0.4
	Height (cm)	-	-		167.8 ± 7.3	164.1 ± 5.0	0.7
	CMJ (cm)	-	-	-	42.7 ± 5.0	42.0 ± 4.0	0.2
	rMSV (%)	-	-	-	95.6 ± 3.4 ***	90.0 ± 1.9	2.5
	rSI (%)	-	-	-	82.7 ± 4.3 **	75.9 ± 4.6	1.5
	rST at early junior age (%)	-	-	-	122.3 ± 2.5 ***	126.7 ± 2.2	-1.9
13 years	Age (years)	13.6 ± 0.3	13.7 ± 0.2	-0.4	13.4 ± 0.3	13.6 ± 0.3	-0.7
	Swim training (hours per week)	9.8 ± 2.3	8.4 ± 3.1	0.5	9.3 ± 1.4	9.4 ± 2.3	-0.1
	Height (cm)	175.4 ± 9.2	176.3 ± 7.0	-0.1	171.2 ± 5.7 *	167.2 ± 5.3	0.8
	CMJ (cm)	51.1 ± 2.0	50.3 ± 4.6	0.2	44.6 ± 4.9	42.4 ± 4.3	0.5
	rMSV (%)	95.2 ± 3.7 ***	86.6 ± 4.5	2.0	96.1 ± 2.7 **	92.2 ± 3.1	1.3
	rSI (%)	77.9 ± 6.4 *	74.5 ± 4.4	0.6	82.7 ± 4.5	80.7 ± 4.2	0.5
	rST at early junior age (%)	123.1 ± 2.2 ***	128.4 ± 3.0	-1.9	119.1 ± 2.6 ***	123.6 ± 2.4	-1.8

		Males (N=47)			Females (N=43)		
		High-performing late juniors	Lower-performing late juniors	Effect sizes	High-performing late juniors	Lower-performing late juniors	Effect sizes
		M ± *SD*	*M* ± *SD*	*d*	*M* ± *SD*	*M* ± *SD*	*d*
14 years	Age (years)	14.6 ± 0.3	14.6 ± 0.2	-0.2	14.5 ± 0.3	14.6 ± 0.3	-0.5
	Swim training (hours per week)	11.7 ± 2.6	10.1 ± 3.3	0.5	11.1 ± 3	10.9 ± 2.8	0.1
	Height (cm)	180.6 ± 9.0	180.1 ± 7.2	0.1	174.0 ± 3.2 *	168.8 ± 4.7	1.2
	CMJ (cm)	52.5 ± 2.0	51.3 ± 4.8	0.3	46.5 ± 3.6 *	42.7 ± 4.1	1.0
	rMSV (%)	97.6 ± 3.1 ***	90.4 ± 3.8	2.0	98.5 ± 2.6 **	94.2 ± 3.3	1.4
	rSI (%)	82.6 ± 7.1 *	78.2 ± 4.2	0.8	86.1 ± 5.4	84.5 ± 2.1	0.5
	rST at early junior age (%)	119.5 ± 2.4 ***	124.3 ± 2.3	-2.1	115.6 ± 1.9 ***	120.1 ± 2.2	-2.1
15 years	Age (years)	15.7 ± 0.2	15.6 ± 0.2	0.6	-	-	-
	Swim training (hours per week)	11.6 ± 3.0	11.3 ± 3.1	0.1	-	-	-
	Height (cm)	186.9 ± 3.7	183.4 ± 7.3	0.6	-	-	-
	CMJ (cm)	54.4 ± 2.4	52.8 ± 4.5	0.4	-	-	-
	rMSV (%)	99.0 ± 2.9 ***	92.5 ± 3.4	2.0	-	-	-
	rSI (%)	89.8 ± 6.7 **	82.3 ± 5.5	1.3	-	-	-
	rST at early junior age (%)	115.2 ± 1.7 ***	121.0 ± 1.9	-3.1	-	-	-

Note. 41 freestyle (20 males); 13 butterfly (7 males); 22 breaststroke (13 males); 14 backstroke (7 males) swimmers. Age refers to the calendar age as of December 31st of the corresponding season. CMJ=countermovement jump; rMSV = relative maximal swimming velocity; rSI = relative stroke index; rST = relative swim time. CMJ, rMSV, rSI, and rST at early and late junior age are reported as predicted values instead of observed values.* $p < 0.05$ (one-tailed); ** $p < 0.01$ (one-tailed); *** $p < 0.001$ (one-tailed).

Anthropometric measures

Swimmers were measured for height, sitting height and body mass with 0.1 cm or 0.1 kg precision. Height was assessed using a stadiometer (Seca, 217, Seca GmbH & Co.KG, Germany), and sitting height was measured using a standard box (height 45 cm) positioned at the stadiometer's base. Body mass was measured using a digital scale (Beurer, GS 300, Beurer GmbH, Germany). Measures were taken twice and conducted by the same two researchers. The mean value was documented. A third measure was taken if the difference between the first two exceeded 0.4 cm. The median was then recorded.

Maturity status was estimated using a non-invasive method developed by Moore et al. (2015). This approach involves sex-specific calculations that determine the maturity offset of young adolescents, expressed in terms of years before or after Peak Height Velocity (YPHV). By subtracting YPHV from a swimmer's chronological age, the predicted age of PHV (APHV) was calculated. However, it is important to acknowledge that accurately measuring biological maturity remains a challenging task, as highlighted by ongoing discussions in the literature that emphasize the complexities involved in this process (Malina et al., 2021)

Countermovement Jump (CMJ) test

Swimmers were instructed to perform two double-leg vertical countermovement jumps (CMJ) with arm swing, which is reported as a valid and reliable test to measure lower body power (Markovic et al., 2004). Lower body power is considered to be of particular importance during starts and turns, as it is in these moments that the lower extremities must generate the greatest impulse to achieve the highest accelerations off the block and wall, respectively (Keiner et al., 2021; Jones et al., 2018; West et al., 2011). The jumps began from an upright position, and there was a 30 s break between each trial to allow the swimmers to return to the starting position. Each trial was recorded with a vertical jump meter (Takei, TKK5406, Takei Scientific Instruments Co.,Ltd, Japan). The maximal jump height (in cm) was taken as indicator of lower body power and taken as outcome measure for further analyses (Gajewski et al. 2018).

Mid-pool sprints

Swimmers were instructed to perform one 25-m distance sprint at maximal swimming velocity. They initiated their effort from the midpoint of a 50-m pool, specifically at the 25-m mark. Starting from a static position, they immediately accelerated to full speed and maintained this pace until they touched the wall, signifying the completion of their effort. Swimmers performed the sprint effort in their best stroke, while wearing racing suits. Sprints were recorded with a digital video camera (HC-X1000 Camrecorder, Panasonic Netherlands, Netherlands), positioned on the lateral side of the pool at 15-m from the start. Kinematic data were collected by means of time video analysis. Maximal swimming velocity was defined as the clean swimming velocity (10-m distance divided by time for the 10-m distance, m/s) between the 10- and 20-m segment of the 25-m trial. Regardless of distance and stroke, this parameter is crucial for any swimmer aiming to touch the wall first (Barbosa et al., 2010), given that clean swimming predominates in (long course) swimming events (Gonjo & Olstad, 2020). Stroke rate (Hz) was calculated as the number of strokes completed by the swimmer during this 10-m segment (Poujade et al., 2002), one stroke rate cycle being defined as the time between the entry of one hand until the following entry of the same hand (Huot-Marchand et al., 2005). Stroke length (m) was calculated as the ratio between swimming velocity over the 10-m segment and the corresponding stroke rate (Poujade et al., 2002). Stroke index (SI), an indirect measure of swimming efficiency, was calculated by multiplying swimming velocity by stroke length. The SI measures the ability of the swimmer to complete a given distance with a particular speed in the fewest possible number of strokes (m^2/s) (Costill et al., 1985). Maximal swimming velocity and SI were taken as outcome measures for further analyses.

Data processing

To enable meaningful comparisons among swimmers specialized in different strokes and distances, outcomes were related to relevant reference values and expressed as a percentage, rather than absolute values (see equation 1). This approach is essential because direct comparisons of absolute values in swim performance and test scores within our sample could potentially lead to misconceptions. For instance, it is widely acknowledged that the breaststroke is inherently slower to perform than the freestyle (Moser et al., 2020). Similarly, when considering distance, it is evident that the duration of an event increases with the length of the distance to travel (Moser et al., 2020). Taking these stroke-specific and distance-related nuances into account ensures a more accurate evaluation of swimmers' capabilities.

Consequently, swim time was related to the prevailing world record (WR), a method initially introduced by Stoter et al. (2019) in speed skating and subsequently applied in competitive swimming (Post et al., 2020a, 2020b). Lower percentages on relative Swim Time (rST) indicated swim performances closer to the WR. Moreover, scores on swimming tests were related to the average start time, turn time, clean swimming velocity and SI of male and female finalists at the European Championships in 2021 (Born et al., 2022). Stroke-specific data of the 100- and 200-m events were used as reference values for sprinters (50-100-m) and middle-distance (200-400-m) swimmers in our sample respectively (see **Appendix A**). Higher percentages on relative maximal swimming velocity (rMSV) and stroke index (rSI) indicate scores more close to the European elite level (set to 100%). For example, the maximal swimming velocity of an early junior male freestyle sprinter (1.85 m/s) was related to the average clean swimming velocity of the 100-m freestyle European male finalists (1.98 m/s), resulting in a rMSV of 93.4% ((1.85/1.98)*100%).

$$relative\ variable\ x = \frac{absolute\ variable\ x}{reference\ value\ x} \times 100\% \qquad \text{(eq. 1)}$$

Data selection

In cases where swimmers had multiple data points within a season, the swimmers' season best rST, rMSV along with the corresponding rSI, CMJ and anthropometric scores were selected for further analyses (see **Appendix B** for number of measurements by performance level group and age category). Any other data were excluded, minimizing the impact of variations in achievements within a season. The median number of between-season observations was n = 2 in males and females.

Defining Performance Level Groups

A higher- and lower-level performance group were defined according to performance trajectories of international elite swimmers, representing a performance level similar to the top 50 swimmers worldwide of the past 5 years (2017-2022 with the exception of 2020, see Post et al., 2020a). Following the approach adopted in previous studies (Stoter et al., 2019; Post et al. (2020b), the maximum season best rST by age category, sex and swim event of these international elite swimmers was used as performance benchmark (%WR, see **Appendix C**). Swimmers whose season best rST at late junior age (males aged 16; females aged 15) fell within the corresponding performance benchmark were categorized as high-performing late juniors and considered to be on track to reach the elite level (16 males; 10 females). Conversely, swimmers who did not meet the performance benchmark were classified as lower-performing late juniors and considered to be off track to reach the elite level (31 males; 33 females). To illustrate, consider a 16-year-old male swimmer competing in the 100m freestyle. If his season best rST is 115.1%, he would be classified in the high-level performance group since it falls within the performance benchmark for 16-year-old males in the 100m freestyle, which is set at 116.3%. However, if his season best rST is 117.8%, he would be classified in the lower-level performance group as it exceeds the corresponding performance benchmark

Statistics

All data were analyzed for males and females separately, using R (R Core Team, 2021). Data were initially screened on outliers (using box plots), normality (using QQ-plots) and homogeneity of variance (using Levene's test). Outliers (16 in males; 19 in females) were acknowledged as a natural occurrence within the population and, consequently, were not removed from the dataset. Normality was violated in males (rST at early and late junior age) and females (height, rMSV and rST at early and late junior age). Homogeneity of variance was assumed with the exception of CMJ (males) and rST at late junior age (males and females).

Cross-tabulation analyses were performed to analyze the relationship between performance level group at late junior (males aged 16; females aged 15) and early junior age (males aged 13; females aged 12). For high- and lower-performing late juniors, mean scores and standard deviations were calculated for swim performance and underlying performance characteristics at the beginning of their junior years (males aged 13; females aged 12). Independent sample t-tests were included to examine between-group differences on age, swim training (hours per week), height, CMJ, rMSV, rSI, rST at early junior age and rST at late junior age (to ensure correct definition of our performance groups). Mann-Whitney U tests were included to examine between-group differences on variables in which assumptions were violated. For all tests, $p < 0.05$ (one-tailed) was considered statistically significant.

To interpret the scores, effect sizes (Cohen's d values) were calculated. An effect size of approximately 0.20 was considered small, while effect sizes of 0.50, 0.80 and 1.20 were considered medium, large and very large, respectively (Cohen, 1988). A sensitivity power analysis confirmed that our statistical tests were sufficiently sensitive to detect significant differences between performance-level groups with a minimum detectable effect size of 0.8 and 0.9 (males and females respectively) (alpha = 0.05, power = 0.80). Statistical tests for measuring invariance were not performed given the nature of our dataset (relatively few observations for many items).

Longitudinal multilevel models were created to describe development of rST, rMSV, rSI and CMJ (dependent variables) as a function of (chronological) age, using the lmer4 package in R (R version 3.6.0). The age effect (which was used as measure for development over time) was not imposed to be identical between high- and lower performing late juniors. Therefore, a nested interaction between age and performance level group at late junior age was included. To represent these two performance level groups in the statistical models, one dummy variable (high-level performance group) was included and the lower-level performance group functioned as reference level. Each swimmer's individual trajectory was accommodated through the estimation of a random intercept model, allowing the intercept to vary between swimmers while remaining constant within measurements of the same swimmer. In sum, the following multilevel model was adopted:

$$Y_{is} = \alpha_i + \beta_1 \times Age_{is} + \beta_2 \times (Age_{is} \times High-level\ performance\ group_i) + u_i + \varepsilon_{is}$$

$$u_i \sim N(0, \sigma_0^2)$$

$$\varepsilon_{is} \sim N(0, \sigma^2) \qquad \text{(eq. 2)}$$

Yis was the dependent variable (e.g., rMSV) for swimming season *s* of swimmer *i*, α_i the intercept of swimmer *i*, Age_{is} the corresponding age value and *High-level performance* $group_i$ the dummy variable indicating whether or not swimmer *i* was in the high-level performance group. The unexplained information was the sum of u_i (between-subject variance) and ε_{is} (residual variance). The models were validated by using visible patterns in residual plots to check violations of homogeneity, normality and independence. Predictor variables were considered significant if the p value of the estimated mean coefficient was smaller than 0.05.

Results

Table 1 shows the descriptive statistics, including effect sizes, of male and female swimmers according to their performance level at late junior age (males aged 17; females aged 16) by age group. High-performing late juniors outscored lower-performing late juniors on rST at late junior age ($p < 0.001$; very large effect sizes), confirming a correct definition of performance level groups in both males and females. Furthermore, high-performing late junior females demonstrated an earlier age of PHV compared to lower-performing females ($p < 0.05$). No significant differences between high- and lower-performing male and female swimmers on age and weekly swim training hours were found ($p > 0.05$). **Figure 2** provides a visual representation of the mean scores, interquartile range, as well as the minimum and maximum scores for age of PHV, height, and swim training hours.

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High-performing late junior males scored significantly higher on rMSV at age 13, 14 and 15 (all $p < 0.001$), rSI at age 13, 14 ($p < 0.05$) and 15 (($p < 0.01$), and rST at age 13,14 and 15 (all $p < 0.001$), compared to lower-performing peers. The effect sizes for rMSV and rST were found to be very large, while for rSI, they showed an increasing trend from medium to very large. Although not statistically significant, high-performing late junior males had higher scores on CMJ (small-to-medium effect sizes) at age 13, 14 and 15, and height at age 15 (medium effect sizes) compared to lower-performing males. Similar scores were found between groups on height at age 13 and 14 (no effect).

High-performing late junior females scored significantly higher on rMSV at age 12, 13 and 14 ($p < 0.001$ at age 12 and 13, $p < 0.01$ at age 14), rSI at age 12 ($p < 0.01$), CMJ at age 14 ($p < 0.05$), height at age 13 and 14 ($p < 0.05$) and rSBT at age 12, 13 and 14 (all $p < 0.001$) compared to lower-performing peers. The effect sizes for rMSV and rST were found to be very large while for CMJ and height the effect sizes were considered large. Although not statistically significant, high-performing late junior females had higher scores on CMJ (small-to-medium effect sizes) at age 12 and 13, and height at age 12 (medium-to-large effect sizes) compared to lower-performing females.

Table 2 shows the cross-tabulation analyses of the relationship between performance level group at late and early junior age of male and female swimmers. At late junior age (16 years), fifteen of the 45 male swimmers (33%) were classified in the high-level performance group. All fifteen high-performing male late juniors (100%) were also categorized as high-performing early juniors (13 years), whereas 27 out of the 42 (64%) high-performing male early juniors switched to the lower-level performance group at late junior age. For females, ten of the 43 swimmers (23%) were classified in the high-level performance group at late junior age (15 years). Eight high-performing female late juniors (80%) were also categorized as high-performing early juniors (12 years), whereas 21 out of the 29 high-performing early junior females (72%) switched to the lower-level performance group at late junior age.

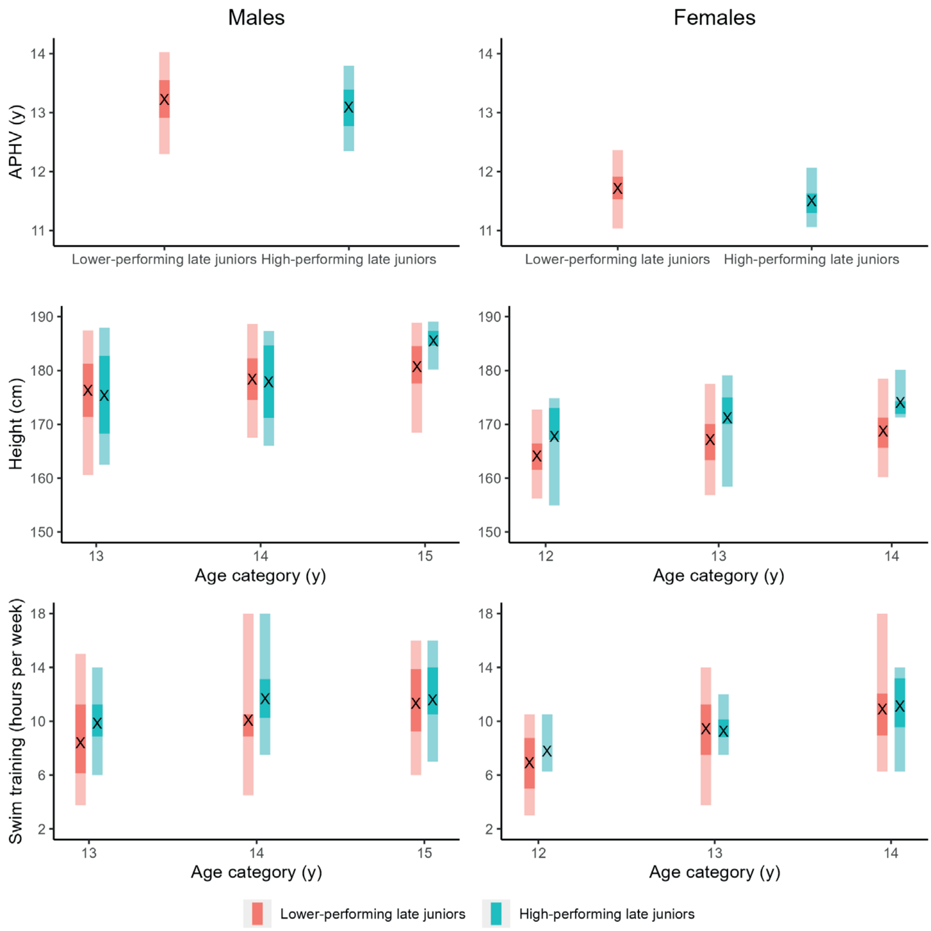

Figure 2. Mean (indicated with X), interquartile range (indicated with darker colors), minimum and maximum (indicated with lighter colors) observed values on age of peak height velocity (APHV), height and swim training hours for males and females according to performance level at late junior age.

Table 2. Cross-tabulation analyses of the relationship between performance level group at early and late junior age of male and female swimmers.

	Total (N)	High-performing early juniors (n)	Lower-performing early juniors (n)
Males	45 (100%)	42 (93%)	3 (7%)
High-performing late juniors	15 (33%)	15 (100%)	0 (0%)
Lower-performing late juniors	30 (67%)	27 (90%)	3 (10%)
Females	43 (100%)	29 (67%)	14 (33%)
High-performing late juniors	10 (23%)	8 (80%)	2 (20%)
Lower-performing late juniors	33 (77%)	21 (64%)	12 (36%)

Note. Performance groups are based on season best performances at age 12 for males and age 11 for females. Two male swimmers (1 high-performing late junior and 1 lower-performing late junior) could not been classified at early junior age due to missing data and left out of this analysis (N=47 adjusted to N=45).

Table 3. Model estimates for male (N=47 with 107 observations) and female (N=43 with 100 observations) swimmers.

	rSBT		rMSV		rSI		CMJ	
	Estimates (S.E.)	*P-value*	*Estimates (S.E.)*	*P-value*	*Estimates (S.E.)*	*P-value*	*Estimates (S.E.)*	*P-value*
Males								
Fixed effects								
Intercept	172.62 (4.56)	**<0.001**	55.51 (7.30)	**<0.001**	10.45 (14.07)	0.230	34.14 (8.92)	**<0.001**
Age	-3.16 (0.31)	**<0.001**	2.26 (0.49)	**<0.001**	4.52 (0.95)	**<0.001**	1.16 (0.60)	**0.029**
Age × high-level performance group	-0.34 (0.07)	**<0.001**	0.53 (0.11)	**<0.001**	0.33 (0.16)	**0.023**	0.07 (0.11)	0.264
Random Effects								
σ^2	4.73		8.66		45.97		17.37	
τ_{00}	8.40		24.18		40.26		20.87	
Marginal R^2 / Conditional R^2	0.61 / 0.86		0.40 / 0.84		0.26 / 0.60		0.05 / 0.57	
Females								
Fixed effects								
Intercept	169.03 (4.66)	**<0.001**	66.86 (5.80)	**<0.001**	23.87 (13.67)	**0.043**	41.63 (7.52)	**<0.001**
Age	-3.31 (0.35)	**<0.001**	1.84 (0.43)	**<0.001**	4.15 (1.02)	**<0.001**	0.04 (0.56)	0.422
Age × high-level performance group	-0.28 (0.08)	**<0.001**	0.29 (0.10)	**0.002**	0.14 (0.19)	0.244	0.18 (0.14)	0.098
Random Effects								
σ^2	5.35		7.14		51.27		10.90	
τ_{00}	6.62		9.81		30.66		21.45	
Marginal R^2 / Conditional R^2	0.55 / 0.80		0.30 / 0.72		0.17 / 0.48		0.03 / 0.67	

Note. "Age" term denotes development of lower-performing seniors. "Age + Age × high-level performance group" denotes development of high-performing swimmers. Abbreviations: rSBT (relative season best time); rMSV (relative maximal sprint velocity); rSI (relative stroke index). Significant predictor variables ($p < 0.05$) are denoted in bold with adjustments made for one-sided hypothesis testing in the calculation of the p value.

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Developmental models according to performance level group at late junior age

Table 3 shows the developmental models on rSBT, rMSV, rSI and CMJ created for males and females. Each model consists of two age effects, which allows for different rates of development between high- and lower-performing late juniors. The “age” term denotes the development of lower-performing late juniors, whereas “age + age × high-level performance group” denotes the development of high-performing late juniors. To illustrate (using the fixed effects of the model only), the rSBT for a high-performing male late junior swimmer at age 14 will be predicted as follows:

$$rSBT = 176.80 + (-3.46 * 14) + (-0.37 * 14) = 123.18 \qquad \text{(eq. 3)}$$

Given the study's primary focus on differences between high- and lower-performing swimmers, particular emphasis will be placed on analyzing the interaction term (age × high-level performance group). A significant interaction term would indicate a faster rate of development of high-performing swimmers compared to their lower-performing peers.

In males, high-performing late junior swimmers showed significant faster progression over time on rSBT (+11%, $p < 0.001$), rMSV (+22%, $p < 0.001$) and rSI (+7%, $p < 0.05$) compared to lower-performing late junior swimmers (+). In females, high-performing senior swimmers showed significant faster progression over time on rSBT (+12%, $p < 0.001$) and rMSV (+20% $p < 0.01$). No significant developmental differences between groups were found on rSI for females and CMJ in males and females ($p > 0.05$). **Figure 3** (males) and **Figure 4** (females) reflect the predicted development of high- and lower-performing late juniors during their pubertal years.

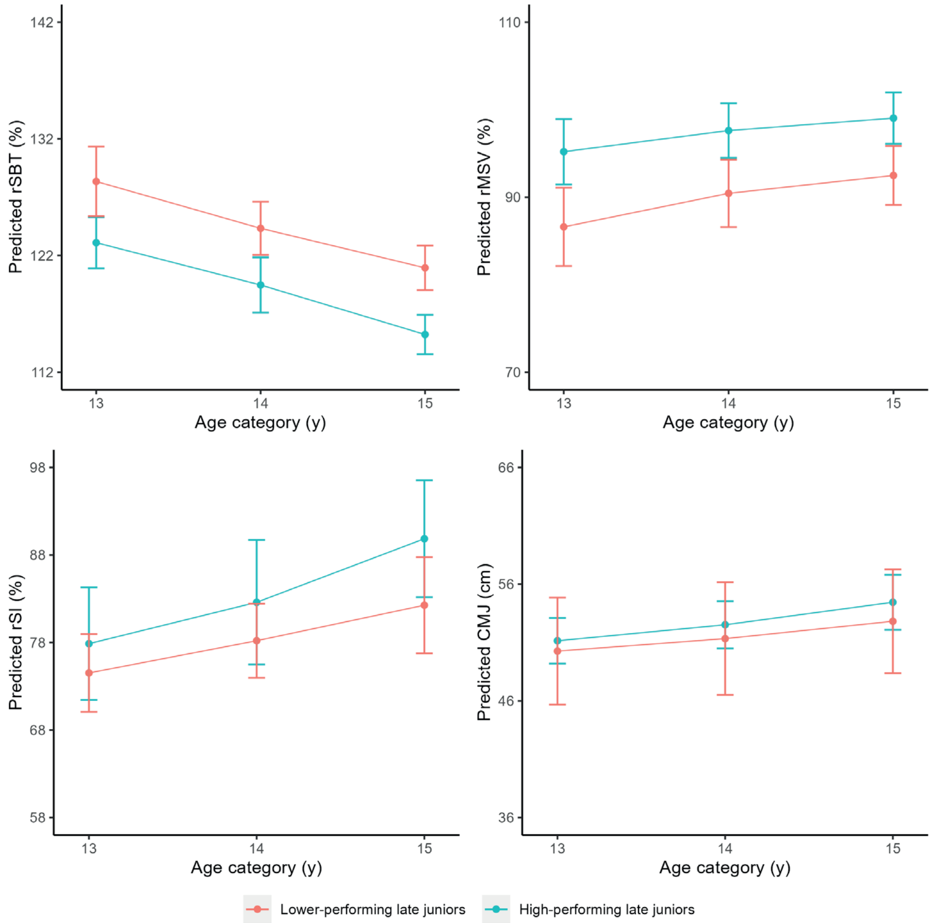

Figure 3. Predicted development as function of age (mean ± SD) of swim performance and underlying performance characteristics in males (N=47 with 107 observations).

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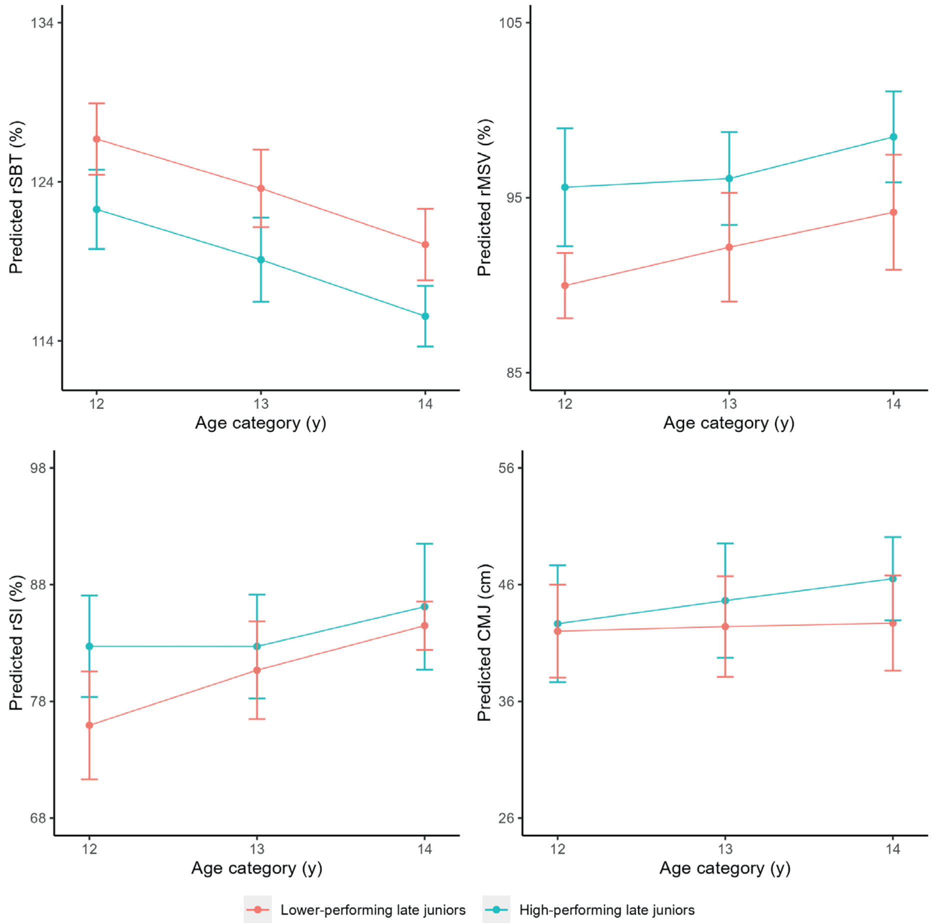

Figure 4. Predicted development as function of age (mean ± SD) of swim performance and underlying performance characteristics in females (N=43 with 100 observations).

Discussion

The present study investigated the development of swim performance and its underlying performance characteristics throughout puberty, differentiating between swimmers who were on track to the elite level (referred to as high-performing late juniors) and those who were not (referred to as lower-performing late juniors) at late junior age (males aged 16; females aged 15). Retrospectively studying these swimmers, we found that high-performing late juniors outperformed their lower-performing peers on most of the assessed underlying performance characteristics during the pubertal years (males aged 13-15; females aged 12-14). Furthermore, high-performing late juniors were characterized with significantly faster development in season best performances, maximal swimming velocity and SI (males only) throughout puberty.

Performance

Our findings showed that all high-performing late junior swimmers (except for two females) were already on track to the elite level at early junior age (males aged 12; females aged 11). Additionally, these swimmers demonstrated significantly faster season best performances throughout puberty (males aged 13-15; females aged 12-14) compared to their lower-performing peers. This trend aligns with the finding that top-elite swimmers (best 8 world-wide) progressively outperformed their lower-performing peers, starting from the age of 12 (Post et al., 2020a). As such, our results suggest that achieving higher levels of swim performance at early junior age may signify a minimal level of proficiency, serving as a prerequisite for further progression towards swimming expertise. This observation aligns with the work of Yustres et al., (2019) in competitive swimming, and research in cycling (Gallo et al., 2022; Mostaert et al., 2022). However, it is important to note that our findings also reveal that only a minority of the high-performing swimmers at early junior age was able to sustain their performance level until the end of puberty (36% in males; 28% in females). This demonstrates that early achievements in itself do not necessarily guarantee successful development towards higher performance levels, a notion supported by previous studies in both competitive swimming and other sports (Brustio et al., 2021; Güllich et al., 2023; Barreiros et al., 2014;). Instead, in line with Brustio et al. (2022), our findings underscore that the significantly faster progression in season best performances shown by high-performing late juniors (+11% in males and +12% in females as reported in our study) holds equal, or perhaps even greater importance than current performance in the advancement towards swimming expertise.

Underlying performance characteristics

Aligning with the progressive trends observed in season best performances, our findings demonstrate that high-performing late junior swimmers had significantly higher levels, as well as faster progression (+22% in males; +20% in females) on maximal swimming velocity compared to lower-performing peers throughout puberty. Furthermore, they exhibited significantly higher levels of stroke index (SI), a measure of technical ability (males aged 12-14, females aged 12), with significantly faster advancements for high-performing late junior males in this aspect as well (+7% in males). Shifting our focus to the land-based tests, we found that high-performing late junior females were significantly taller at age 13 and 14, and demonstrated higher CMJ at age 14 compared to lower-performing peers, whereas surprisingly, no significant between-group differences were found for males on these variables.

Taken together, swimmers who are on track to the elite level at late junior age (males aged 16; females aged 15) are characterized with the ability to attain higher swimming speed with equal (females aged 13-14) or even better levels of technical efficiency than lower-performing juniors throughout puberty. Given that competitive swimming centers around maintaining optimal power output in an efficient and skillful manner throughout the event (Miyashita, 1996), this could be a critical factor in the attainment of swimming expertise. Additionally, being taller, particularly as a female aged 13-14, may be a beneficial characteristic for superior swim performances post-puberty. This advantage can be attributed to the strong relationship between longer lengths, such as height, and increased stroke length and speed (Morais et al., 2021).

Maturation and training

Considering our findings, it is important to acknowledge that performance and its underlying performance characteristics may be influenced by inter-individual differences in timing of PHV as well as training hours. Regarding the former, we found a significantly earlier onset of PHV in high performing late junior females (~2.4 months) as well as within-group variations of 1.0 to 1.5 years in age of PHV (females and males respectively). While we cannot disregard the possibility that relatively early maturing swimmers in our study may have experienced physical advantages compared to relatively later maturing swimmers, we do not expect that these variations significantly affected our findings. This anticipation is grounded in the observation that the between- and within-group differences are considerably small, particularly compared to the five to six years difference between players' chronological and biological age reported by Johnson et al. (2009).

In the context of training, we observed that high-performing late junior swimmers tend to engage in slightly more swim training hours per week, with this trend being more pronounced among males compared to females. Interestingly, the minimum training hours per week are consistently higher among high-performing late juniors. Within performance level groups , we noticed differences of more than ten hours between swimmers who had the lowest and highest amount of swim training per week. Given that the total amount of (deliberate) training is correlated with attainment (Baker & Young 2014), it is likely that such notable differences may advantaged swimmers with access to a higher number of training compared to those with fewer hours. However, while we acknowledge that these benefits may be reflected in our results on the individual level, we expect that the impact on our overall findings will be limited given the subtle and minor variations observed between high- and lower-performing swimmers.

Strengths and limitations

The present study comprised a wide range of talented swimmers as we included participants from the Dutch Junior National Championships, rather than solely inviting swimmers from national talent development program, who are typically the top performers of their age group. We followed this relatively large and heterogenous group of swimmers over time (varying from 6 to 18 months) and monitored their development on swim performance and multiple underlying performance characteristics. Using this multidimensional and longitudinal design, which is scarce in literature, we acquired insights into swimmers' developmental patterns (skill levels and progression rates) during the pubertal years.

By comparing the scores of maximal swimming velocity and SI to the reference values of international senior elite swimmers, we not only enabled comparisons between swimmers specializing in different events but also gained insights into a swimmer's position relative to the standard set by these top performers. Furthermore, we created performance level groups based on a swimmer's performance level at late junior age relative to the performances of international senior elite swimmers of the same age in the past. While this approach doesn't make direct predictions about senior performances, our classification of performance level groups does take future achievements into account. As a result, our findings may provide insight into swimmer's potential for later success, which offers scientific and practical value for talent development in swimming.

However, when interpreting the results, it is important to acknowledge that our findings pertain to pubertal swimmers (males aged 13-15; females aged 12-14) who qualified for the Dutch National Junior Championships. Considering that our measurements were conducted during this particular event, it is important to recognize that swimmers who did not meet the qualification criteria were unable to participate in the measurements. Furthermore, reflected by the lower mean ages of PHV (13.1 years for males; 11.6 years for females) compared to the average ages of 14 in males and 12 in females (Malina et al., 2004a), we observed an overrepresentation of early-maturing swimmers throughout the sample. In light of the physical advantages associated with early maturation, it is possible that the swimmers in our study were more likely to qualify for the Dutch National Junior Championships compared to late-maturing swimmers. This potentially introduces a survivorship bias in our results (Baker et al., 2022).

Moreover, we examined swimmers who are currently in the midst of their development, analyzing a limited set of underlying performance characteristics. Notably, we did not examine potential interactions between variables which are undoubtedly at play (Barbosa et al., 2010; Abbott et al., 2021b). Furthermore, given the dynamic nature of performance development, the relative contribution of underlying performance characteristics may vary among different specializations in our sample and change over time (Vaeyens et al., 2008; Morais et al.,2015). For example, lower body power (measured as jump height), is considered to be more critical for swimmers oriented towards sprinting (Keiner et al., 2021). In terms of timing, it may emerge as a more distinguishing factor in later stages of development, particularly after puberty, as training programs tend to place a greater emphasis on the development of strength and power (KNZB, 2023). Therefore, it is important to highlight that the present study captures merely a glimpse of the long and complex developmental pathway towards swimming expertise, leaving a lot of opportunities for future research to expand upon our findings.

Perspective

The present study enhances our understanding of advancement towards elite level swimming performance. Specifically, it underscores the significant role of levels and progression of maximal swimming velocity, SI, and season best performances throughout puberty in males aged 13-15 and females aged 12-14. In addition, height and CMJ emerged as noteworthy characteristics in females. Coaches could focus on developing these factors and monitor their swimmers' progression towards the elite level in relation to the developmental patterns of high-performing late juniors. However, coaches should consider these findings as a starting point for further development rather than an endpoint, and take inter-individual differences in maturation and training into account when evaluating swimmers' current performance and future potential.

Moreover, our findings show that differences between high- and lower-performing juniors manifest at least at early junior age (males aged 13; females aged 12) and emphasize the difficulty of closing that gap thereafter. Therefore, it would be interesting to further investigate swimmers' development from the start of their career. Furthermore, given that high-performing late juniors still have a long road to go before reaching the top, it is recommended to continue monitoring swimmers after puberty. In both cases, gaining insight into swimmers' training programs, including factors such as the number of sessions, training hours and meters per week, the employed training methods (Nugent et al., 2017), and indicators of the quality of training (Post et al., 2022) would be highly valuable. This is essential to not only further unravel but also ensure sustained progression towards elite level swimming performance.

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Appendices

Appendix A. References values of key performance indicators of European male and female finalists (retrieved from Born et al., 2022).

	Clean swimming speed (m/s)	Stroke index
Males (100-m events)		
Backstroke	1.77	3.81
Breaststroke	1.60	2.80
Butterfly	1.84	3.64
Freestyle	1.98	4.63
Males (200-m events)		
Backstroke	1.62	3.81
Breaststroke	1.48	3.71
Butterfly	1.68	3.41
Freestyle	1.81	4.54
Females (100-m events)		
Backstroke	1.58	3.11
Breaststroke	1.43	2.56
Butterfly	1.63	2.84
Freestyle	1.77	3.84
Females (200-m events)		
Backstroke	1.48	3.23
Breaststroke	1.34	3.04
Butterfly	1.50	2.63
Freestyle	1.64	3.69

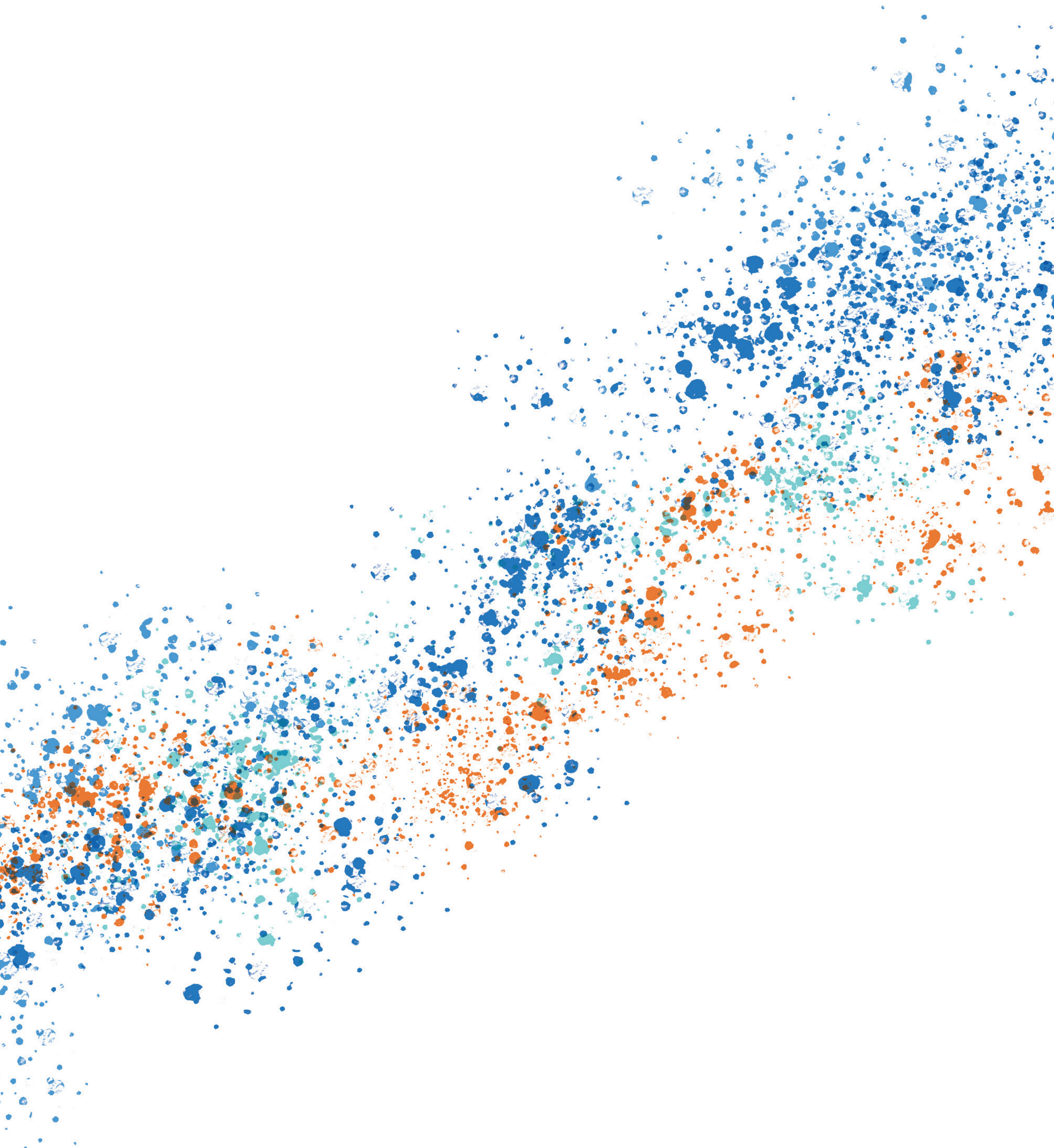
Appendix B. Number of swimmers measured in one through three seasons and number of season best observations per age category during the pubertal years.

	N swimmers	n swimmers measured for 2 seasons	n swimmers measured for 3 seasons	N obs.	n obs. (at age 11)	n obs. (at age 12)	n obs. (at age 13)	n obs. (at age 14)	n obs. (at age 15)
Males (N=47)									
High-performing late juniors	16	11	5	37	-	0	12	15	10
Lower-performing late juniors	31	23	8	70	-	9	19	23	19
Females (N=43)									
High-performing late juniors	10	6	4	24	2	6	10	6	-
Lower-performing late juniors	33	23	10	76	13	20	27	16	-
Total	90	63	27	207	15	35	68	60	29

Note. N swimmers = total number of unique swimmers participating in the study; n swimmers = number of swimmers measured in one through three seasons; N obs. = total number of season best observations; n obs. = number of season best observations per age category.

Appendix C. Performance benchmarks (%WR) by age category, sex and swim event derived from international elite swimmers.

	Event	Age category	Performance benchmark (%WR)
Males	50 Backstroke	16	117.9
	100 Backstroke	16	116.8
	200 Backstroke	16	114.3
	50 Breaststroke	16	118.4
	100 Breaststroke	16	117.6
	200 Breaststroke	16	115.3
	50 Butterfly	16	117.8
	100 Butterfly	16	116.6
	200 Butterfly	16	117.5
	50 Freestyle	16	117.7
	100 Freestyle	16	116.3
	200 Freestyle	16	116.0
	400 Freestyle	16	114.3
	200 Medley	16	114.9
	400 Medley	16	114.5
Females	50 Backstroke	15	113.9
	100 Backstroke	15	114.4
	200 Backstroke	15	115.2
	50 Breaststroke	15	117.7
	100 Breaststroke	15	115.8
	200 Breaststroke	15	117.4
	50 Butterfly	15	120.3
	100 Butterfly	15	118.7
	200 Butterfly	15	114.6
	50 Freestyle	15	115.9
	100 Freestyle	15	115.0
	200 Freestyle	15	112.2
	400 Freestyle	15	112.7
	200 Medley	15	114.1
	400 Medley	15	113.9



Chapter 8

General discussion

The aim of this thesis was to gain a deeper understanding of the pathway to swimming expertise. Throughout six studies, we examined both swim performance and underlying performance characteristics linked to the swimmer using a longitudinal and multidimensional approach. The results offer a glimpse into the key characteristics and corresponding developmental patterns that distinguish swimmers on track to reach the elite level from their lower-performing peers who, while off track, still attained success at the national level. This revealed two athletic profiles – one for males, and one for females. These athletic profiles, presented in **Figure 1 and 2**, provide a visual summary of this thesis and set the stage for the upcoming discussion. Beyond contributing to a refined scientific understanding, our findings hold the potential to significantly improve talent identification, selection and development processes in swimming practice.

The foundation of the athletic profiles

The findings of this thesis, and by extension, the athletic profiles, are grounded in a well-founded methodology characterized by three specific strengths. These strengths revolve around the definition of performance level groups, which further subdivided talented swimmers into more specific categories, alongside the specific way of data processing throughout the chapters. This approach now allows us to derive valuable insights from the wide range of studies presented in this thesis.

Firstly, the criteria for defining performance level groups were directly linked to the elite level, and remained consistent across all chapters. The term "elite level" in this context refers to swimmers whose performance aligns with the fastest 50 swimmers worldwide in their respective event. However, this classification is suitable only when we can reasonably assume that swimmers are close to their age of peak performance, which is typically around the age of 22 for females and 24 for males (Allen et al., 2014). While this condition applied to **Chapters 2 through 4** where we investigated established, international senior swimmers, it did not hold for **Chapters 5 through 7** where we examined aspiring, national youth swimmers. In the latter case, it is quite likely that these swimmers have not reached their full potential yet. Therefore, **in Chapters 5 through 7**, we explicitly categorized swimmers as either on track or off track to reach the elite level, relying on benchmarks derived from the performance development of elite swimmers established in **Chapter 2**. These benchmarks accounted for variations in swimmers' age, sex and event.

Second, the classification of performance level groups did take future achievements into account. That is, swimmers were categorized into performance level groups only after undergoing a critical developmental phase – specifically, after puberty, following the late-junior-to-early-senior transition and at the age of peak performance. This approach contrasts with assigning them based solely on their current performance levels at the time of data collection. Subsequently, we conducted a retrospective analysis of their development up to the point of classification. As a result, the athletic profiles describe the developmental trajectory of swimmers known to have achieved higher performance levels later in their careers (i.e. on track to reach the elite level) compared to their lower-performing peers who attained success at the national level but were not on track to reach the elite level. This provides valuable information about which characteristics at an earlier time-point may contribute towards achieving the elite level, including their corresponding levels and progression.

Third, whenever possible, collected data were related to relevant reference values of elite swimmers and expressed as relative rather than absolute values. Season best times were related to the prevailing world record (WR) and scores on swimming tests were related to the average start time, turn time, clean swimming velocity and SI of male and female finalists at the European Championships in 2021 (Born et al., 2022). This approach accounts for the evolution of competitive swimming marked by the continuous improvements in world records, and allows for meaningful comparisons among swimmers specializing in different events or emerging from diverse cohorts. Moreover, it provides insights into aspiring youth swimmers' position relative to the international senior standard on both swim performance as well as underlying components of the race.

Collectively, with this strong foundation rooted in meaningful criteria for defining performance level groups, as well as evaluating swimmer's capabilities in relation to the elite level, we are confident in our ability to draw the athletic profiles that relate to the successful progression towards achieving a performance level comparable to the world's top 50 swimmers.

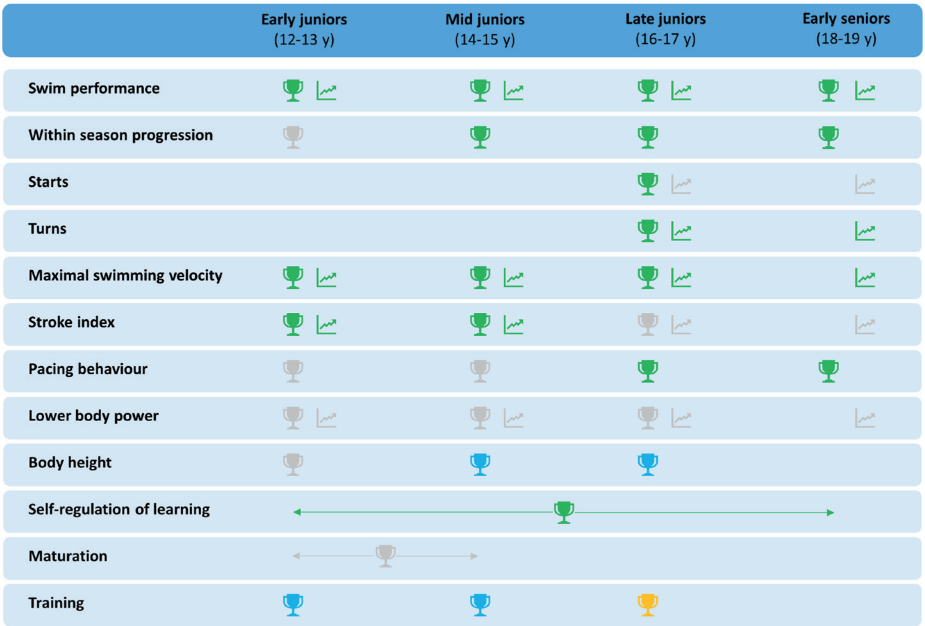


Figure 1. Athletic profile of male swimmers on track to reach the elite level.

Note. indicates assessment in terms of proficiency level; indicates assessment in terms of progression; green symbols indicate significantly better scores (p <0.05) for swimmers on track to the elite level compared to those off track, accompanied by effect sizes ranging from medium to extremely large; blue and orange symbols suggest a trend of respectively higher and lower scores with medium to large effect sizes for swimmers on track to the elite level compared to those off track, although these differences do not reach statistical significance; grey symbols indicate no significant differences between groups accompanied by negligible effect sizes.

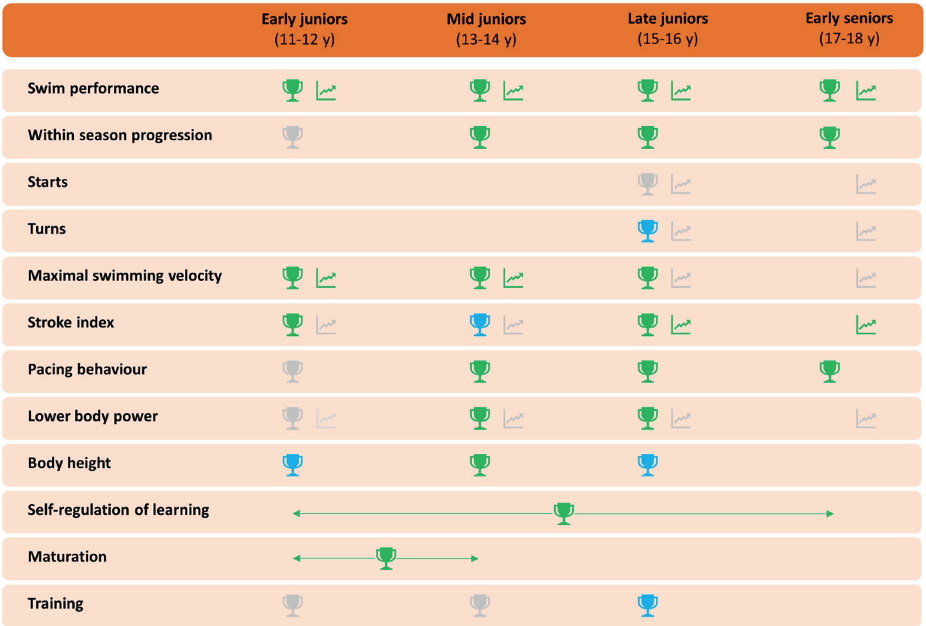


Figure 2. Athletic profile of female swimmers on track to reach the elite level.

Note. indicates assessment in terms of proficiency level; indicates assessment in terms of progression; green symbols indicate significantly better scores ($p < 0.05$) for swimmers on track to the elite level compared to those off track, accompanied by effect sizes ranging from medium to extremely large; blue and orange symbols suggest a trend of respectively higher and lower scores with medium to large effect sizes for swimmers on track to the elite level compared to those off track, although these differences do not reach statistical significance; grey symbols indicate no significant differences between groups accompanied by negligible effect sizes.

Overarching insights on the pathway to swimming expertise

It is apparent from this thesis that swimmers on track to the elite level are generally characterized by athletic profiles that set them apart from their lower-performing peers, who attained success at the national level but were off track to reach the elite level. Examining these profiles from a broader perspective by interconnecting and integrating the findings from all chapters, three overarching insights emerge regarding the pathway to swimming expertise.

Level of swim performance matters, but so does progression

The findings of this thesis highlight a consistent trend: swimmers who reached higher levels of performance (in terms of season best times) later in their career consistently outperformed their lower-level peers at earlier stages of development (**Chapters 2,6 and 7**). Moreover, these higher levels of swim performance (i.e. being on track) at younger ages seem to reflect a minimum level of proficiency necessary to progress to the elite level. However, it is important to note that these early achievements in itself do not necessarily guarantee successful development towards higher performance levels. This is evident in the fact that only a minority of swimmers who excelled in their early careers were able to sustain their performance levels as they advanced. Those who did so, showed significantly faster progression in swim performances between seasons (**Chapters 6 and 7**) and within seasons (**Chapter 3**). As such, we argue that once swimmers are on track to the elite level, their ability to improve over time holds equal, or perhaps even greater importance than their current performance in the advancement towards swimming expertise.

Proficiency is propelled by all dimensions

Swimmers on track to the elite level were not merely proficient in terms of season best times; rather, they excelled on all fronts throughout their career, outperforming their lower-performing peers on a comprehensive multidimensional profile (see Figures 1 and 2). This is line with the notion that the progression of swim performance is driven by the advancements of underlying performance characteristics (e.g., anthropometric, physiological, psychological, technical and tactical variables) linked to the swimmer (Elferink-Gemser & Visscher, 2012; Morais et al., 2017; Barbosa et al., 2019). Moreover, the distinguishing characteristics observed varied across developmental phases, building upon the findings of Morais et al. (2015) who reported similar results within a single season. This reinforces the notion that there may be potential shifts in the relative importance of underlying performance characteristics in relation to levels of swim performance over time. Nonetheless, a defining factor that consistently distinguished swimmers on track from their lower-performing peers was maximal swimming velocity - a critical parameter in which they significantly excelled. During the pubertal years, levels of maximal swimming velocity were within 5% of the elite standard, whereas at late junior age, swimmers on track had already exceeded this standard by 1%. However, while this is an indisputable factor in both males and females, it remains essential to note that the advantage for swimmers on track to the elite level results from the combination of multiple characteristics, along with specific levels and progression rates.

Catalysts for progression

From the age of twelve onwards, our studies consistently revealed improvements in both swim performance and underlying performance characteristics. These progressions are undoubtedly influenced by growth and maturation processes (Abbott et al., 2021; Malina et al., 2004; Morais et al., 2022), along with an increase in training hours (Morais et al., 2017; Nugent et al., 2017; Young et al., 2020). However, beyond these factors, self-regulation of learning (SRL) is proposed as another important variable on athlete's capacity to improve. This notion is supported by the findings from **Chapter 5**, where both levels and progression of swim performance were associated with the engagement in training-centered SRL processes. Particularly, we found that swimmers on track to the elite level reflected more frequently on their strengths and weaknesses during training sessions and carefully assessed which tasks to expend effort in rather than expending effort in all situations. Moreover, they more frequently evaluated their training process and outcomes achieved after training.

The higher engagement in these SRL subprocesses suggests that swimmers on track to the elite level may learn and train in a more efficient and effective way, and therefore, benefit more from training. This may explain, among other factors, why swimmers on track to the elite level exhibit higher levels of proficiency and progression, even in the absence of significant between-group differences in maturation and training compared to lower-performing peers as observed in **Chapters 6 and 7**. The advantages of being more actively involved in the learning process in and out the water may become even more pronounced after puberty, especially during the late-junior to early-senior transition. In this critical phase, improvements are no longer self-evident due to the natural slow down in growth and maturation processes, coupled with nearing maximum training hours. Consequently, to avoid stagnation, the ability to derive greater benefits from training is likely to become even more crucial as swimmers progress further in their careers and approach their age of peak performance.

Athletic profiles are specific for males and females

The findings of this thesis point out crucial differences between male and female swimmers on track to the elite level. This underscores the importance of recognizing that findings from male swimmers cannot be directly extrapolated to females, emphasizing the need for sex-specific considerations.

While both males and females on track to the elite level are characterized with faster season best times from early junior age onwards, a noticeable one-to-two-year gap between sexes emerged up to the late junior years (see **Chapter 2**). This gap, marked by higher performance levels for females, remains consistent across studies examining the developmental pathways of international, elite swimmers and Dutch youth swimmers. The lead-start for females aligns with the earlier onset of physical maturation compared to males, providing objective data demonstrating its impact throughout adolescence.

A closer examination of the underlying performance characteristics reveals that males and females distinguished themselves from lower-performing peers on different factors of swim performance. Specifically, during the pubertal years, females on track set themselves apart from lower-performing peers on height and lower body power, whereas males did not. Moreover, the faster progression in season best times among females is primarily associated with solely maximal swimming velocity rather than SI. This reinforces the notion that during the pubertal years, females differentiate themselves on the more physical aspects compared to males.

At late junior age, differences between males and females appear regarding their proficiency in crucial race components. Males on track outperformed their lower-performing peers on starts and turns, whereas no between-group differences were found in females. Conversely, females on track distinguish themselves on SI, demonstrating considerably higher swimming efficiency than males, despite having comparable levels of maximal swimming velocity at late junior age. Moreover, given the significant progression of SI during the late junior to early senior transition in females, their improvements in season best times seem to be particularly related to enhancements in swimming efficiency as opposed to the pubertal years. As males demonstrated faster improvements in maximal swimming velocity and turns, their progress is likely associated with power output variables in the water rather than swimming efficiency.

Considerations and limitations

Considering this thesis, it is important to acknowledge certain considerations and limitations. First, our findings stem from retrospective analyses, and therefore describe the general developmental patterns of swimmers up to their highest level of performance in their careers thus far. As we did not make direct predictions about swim performances in adulthood, it is crucial to understand that our results do not prescribe and dictate future development. Instead, they offer insights for coaches to guide, evaluate and optimize a swimmer’s developmental trajectory.

Second, given the multitude of factors contributing to swim performance, including both measurable and intangible elements, it is important to note that we deliberately concentrated on a specific set of factors linked to the swimmer, excluding considerations of the environment. Moreover, while we adopted a multidimensional approach by examining factors representing relevant anthropometrical, physiological, psychological, technical and tactical aspects, our analyses focused on studying each of the underlying performance characteristics in isolation. Yet, it's important to acknowledge that potential interactions between these variables are undoubtedly in play (Barbosa et al., 2010; Abbott et al., 2021), such as the proposed relationship pacing behavior and SRL (Elferink-Gemser and Hettinga, 2017).

Third, this thesis captures merely glimpse of the long and complex pathway towards swimming expertise for a specific group of swimmers. While **Chapters 2 through 4** mapped out the developmental trajectory of 100m- and 200m freestyle swimmers from puberty to adulthood, the same level of homogeneity and comprehensiveness was not achieved in **Chapters 5 through 7**. In these later chapters, we longitudinally followed sprint and middle-distance swimmers, performing in different strokes, over two separate, developmental phases: from their early to late junior years, and from their late junior to early senior years. However, we do acknowledge that, if possible, studies should strive to capture the developmental pathway for as long as possible, preferably incorporating event-specific analyses. At the same time, based on our own research, we are well aware of the challenges presented by the small sample sizes inherent in elite sports, as well as the complexities of conducting longitudinal studies. Repeatedly measuring the same swimmer over multiple years demands strong commitment from both scientists and coaches, alongside a measurement protocol that minimally disrupts training time while maintaining scientific rigor. The COVID-19 pandemic undoubtedly heightened the difficulty of this process, significantly impacting our ability to collect data on talented swimmers.

Future directions

This thesis's insights regarding the pathway to swimming expertise establish a solid foundation for future studies, with three specific directions explored in this section. These directions should be considered as complementary to the longitudinal and multidimensional tracking of swimmers over time, addressing persisting gaps in our understanding, as illustrated by the athletic profiles. Other underlying performance characteristics such as measures of hydrodynamics, power output in the water and aerobic capacity, as well as psychological characteristics that were not investigated in this study, are recommended to be included in such analyses as well.

The first direction for future research is to delve deeper into factors that facilitate or hinder progression, considering both variables related to the swimmer, as well as environmental ones. For instance, it would be interesting to further specify general developmental patterns in relation to swimmers' timing of maturation. Furthermore, gaining insight into swimmers’ (multidimensional) training programs, including physical and psychological load and recovery, the employed training methods, and indicators of the quality of training would be highly valuable. This is essential to not only further unravel but also ensure sustained progression towards elite level swimming performance. Last, it becomes essential to explore the efficacy of talent development environments in which swimmers participate, as environmental factors prove to be more controllable than innate talent in influencing swimmers’ development and potential success (Hall et al., 2019; Henriksen et al., 2010; Henriksen & Stambulova, 2023).

The second direction involves gaining a more profound understanding into the relationship between changes in underlying performance characteristics and corresponding shifts in swim performances over time. An option worth exploring involves constructing age-related multilevel models that predict performance using multiple underlying performance characteristics. By comparing estimates between these models over time, insights can be gained into the relative importance of each underlying characteristic in relation to swim performance at different stages of development. However, due to the dynamic nature of performance development, the significance of these characteristics may change not only with age but also with the swimmer's (future) performance level and specialization. Including these factors into modeling would be interesting. However, in this effort, it is crucial that the study sample remains largely intact over time, which is an extremely challenging aspect of talent development research conducted over several years. Moreover, to the best of our knowledge, statistical analysis that integrate all of these components while differentiating between small-sized groups have yet to be developed. Nevertheless, these analyses could provide a more direct and prospective understanding of the factors influencing and predicting swim performance towards the elite level, giving practical insights into which aspects when to improve and what changes to expect.

The third direction entails a more detailed examination, delving into the complex interactions between underlying performance characteristics in relation to swim performance. For example, exploring the relation between lower body power and starts and turns (Jones et al., 2018), can provide valuable insights about the mechanisms and hierarchies underlying the development of swim performance. Moreover, our results show large standard deviations in most of the underlying factors, suggesting that performance levels are related to unique, individualistic combinations in which weaker points can be compensated with stronger points, known as the compensation phenomenon (Vaeyens et al. 2008). Take, for example, a junior female swimmer with lower scores on stroke index, but who excels at starts and turns. While her lower efficiency may not hinder her performance at late junior age, it could pose a challenge as she progresses to the senior level, where faster starts and turns alone may not suffice to overcome this limitation. Future studies could further explore on this, as it can be expected that even the relatively weaker points of a swimmers’ performance require a minimal level of proficiency.

Recommendations for practice

In addition to advancing the scientific understanding of the pathway towards swimming expertise, this thesis introduces methods and insights that may serve as valuable tools in talent identification and development processes in swimming practice and other sports. Fundamental to every recommendation is the awareness that identifying and developing talented swimmers is inherently complex. This complexity arises from the highly individual, emergent, dynamic and multidimensional nature of athlete development, which is influenced by its environment (Baker et al., 2019; Henriksen & Stambulova, 2023; Till et al., 2020), a notion underscored by this thesis' findings. The following recommendations are formulated to promote and maintain an approach that acknowledges the complexity of athlete development, fostering a much-needed individualized perspective.

Move beyond season best times and unravel swim performance through consistent testing

A profound understanding of the contributing factors underlying swim performance, i.e. the process leading up to the result, is crucial for coaches to accurately assess a swimmer's potential, identify specific areas for improvement, and consequently optimize talent identification and development processes. Regularly performing tests and measurements on underlying performance characteristics over time is a fundamental component in this effort. Of course, it is essential to integrate testing and measurements seamlessly into daily practice without unnecessarily consuming excessive time. Therefore, it is crucial to select relevant tests that offer meaningful insights. Considering the findings from this thesis, we propose to monitor all measured variables in this thesis and to evaluate them during talent identification and development processes. Moreover, while testing may primarily serve practical and short-term improvement purposes with regard to gaining more insight into swim performance, collaborating with higher education and universities, and participating in research projects is recommended. This collaborative approach not only facilitates data collection, but also allows for long-term insights at the group level, complementing the close monitoring of individual swimmers. This collaborative effort could create a mutually beneficial situation, optimizing both practice and scientific understanding.

Understand the target and evaluate current abilities in relation to relevant reference values

After gaining a comprehensive understanding of a swimmer's current performance, the next step is to assess how their abilities align to swimming expertise. This requires coaches to comprehend the demands associated with performing at the highest level, extending beyond the mere awareness of swim times corresponding with international podium standards. Indeed, a clear idea about the general performance development of swimmers who have achieved, or are successfully on their way to get there, is needed. In addition to swim times, this includes a multidimensional profile with levels and progression rates of anthropometrics, physiological, psychological, technical and tactical aspects.

The findings of this thesis assist in this effort by providing athletic profiles that relate to successful progression towards the elite level. These profiles highlight which underlying characteristics may be of particular importance during a specific developmental phase. Coaches and swimmers can use this information to focus on developing these underlying characteristics accordingly. Moreover, concrete insights into the levels and progression rates of swim performance and its underlying performance characteristics across various developmental phases of swimmers on track to the elite level are provided.

With regard to the development of season best times between within seasons, **Chapter 2 and 3** describe the general pathway towards the elite level, whereas the formula's in **Chapter 4, 6 and 7** model the development of underlying performance characteristics in terms of pacing behavior, maximal swimming velocity, SI, starts, turns and lower body power of swimmers on track to the elite level. These insights, summarized in **Appendix A and B**, may function as guideline for coaches and assist them a more objective and evidence-informed evaluation of their swimmers' abilities. That is, the provided developmental patterns give a more clear indication of the meaning of a swimmers' levels and progression of season best times and underlying performance characteristics in relation to advancements towards the elite level. However, coaches should perceive analyses like these as a starting point rather than an endpoint for further development, and take inter-individual differences in sex, maturation and training into account when evaluating swimmers' current performance and future potential. Moreover, it is important to be aware that developmental trajectories provided in this thesis are dynamic, and should be updated regularly as the sport of swimming is constantly evolving.

Use the power of self-regulated learning to keep improving

While the first two recommendations focused on analyzing and evaluating swimmers' abilities, the last recommendation delves into the ongoing process of improvement that takes place (or not) after testing and assessment. As indicated in **Chapter 5**, self-regulation of learning plays a crucial role in this context. Instead of relying solely on natural progression due to growth and maturation or increased training hours, this factor can benefit swimmers consistently, making SRL an inherent strength that must be maximized. As coaches can play a vital role in learning and stimulating SRL in swimmers, we recommend that they intentionally include SRL in daily practice, just as they do with technique drills and physical conditioning. During training, coaches could encourage swimmers to reflect more frequently on their strengths and weaknesses, for example by asking questions such as "What went well and why?" Additionally, they can assist swimmers in directing their focus and efforts towards the most crucial tasks. After training, coaches could stimulate evaluation by allowing swimmers to assess their training outcomes in relation to their goals, for example by assigning a score between the 1-10. Subsequently, asking follow up questions such as: “What needs to happen to achieve a higher score?”, or “What contributed to the current score?” can further enhance the evaluation process. In this way, SRL may become a powerful skill for improvement, benefitting the swimmers throughout their entire career. Moreover, embracing the SRL process is not only relevant for swimmers but may be also essential for coaches seeking to improve their talent development programs. In this context, the saying "practice what you preach" appears to be particularly accurate.

Concluding remarks

This thesis contributes to a more nuanced, fine-grained and concrete understanding of the pathway towards swimming expertise, emphasizing that talent identification and development is not an either-or scenario. Instead, it's a both-and situation in which the truth lies in shades of grey. Indeed, our findings highlight the importance of early achievements, suggesting that season best times at an earlier stage in the career could potentially serve as an indicator of future success. At the same time, it is crucial to note that being the absolute best at junior age does not appear to be a strict requirement.

What does seem to be essential is achieving a minimal level of swim performance (i.e. being on track) within each age category. While most swimmers within our sample achieved this during early- and mid-junior age, only a minority of those on track to the elite level during the pubertal years sustained this trajectory into their later careers. Those who did, distinguished themselves on a multidimensional profile, exhibiting higher levels and faster rates of progression on specific variables during puberty and late-junior-to-early-senior transition. These athletic profiles, including anthropometrics, physiological, psychological, technical and tactical aspects, differed within developmental stages and between males and females.

Collectively, this thesis underscores the necessity of moving beyond current season best times as the only source of information in talent identification and development practices. Instead, it advocates for continuous monitoring of individual swimmers’ development, focusing on the variables within the athletic profiles. Moreover, the developmental patterns derived from our studies provide a basis for evaluating swimmers’ proficiency and progression in relation to the elite level. These objective and evidence-informed insights demonstrate the substantial value of multidimensional and longitudinal research for sport practice. Finally, this thesis highlights the role of self-regulation of learning in swimmers’ ability to continuously improve, emphasizing the importance of prioritizing, encouraging and fostering swimmers’ active engagement in their own developmental processes in daily practice.

Appendices

Appendix A. Reference values for the athletic profile of male swimmers on track to reach the elite level, categorized by age.

	Established, international senior elite male swimmers						
	13	**14**	**15**	**16**	**17**	**18**	**19**
Minimal level of swim performance (%WR)	136.1	126.4	120.5	116.1	113.2	111.5	110.2
Mean swim performance (%WR)	121.3 ± 1.6	114.7 ± 1.2	111.0 ± 1.0	108.3 ± 0.8	106.8 ± 0.7	106.0 ± 0.8	105.3 ± 0.7
Within season progression (%)	19.0 ± 3.0	22.4 ± 7.4	20.2 ± 4.2	25.0 ± 5.0	26.6 ± 3.4	27.0 ± 4.5	29.6 ± 3.3
Pacing behavior (50-100m %)	48.31 - 51.69	48.29 - 51.71	48.27 - 51.73	48.25 - 51.75	48.23 - 51.77	48.21 - 51.79	48.20 - 51.80
Pacing behavior (50-100-150-200m %)	23.21 - 25.42 - 26.01 - 25.35	23.24 - 25.40 - 25.97 - 25.38	23.27 - 25.39 - 25.93 - 25.41	23.29 - 25.37 - 25.90 - 25.44	23.32 - 25.35 - 25.86 - 25.47	23.34 - 25.34 - 25.83 - 25.49	23.36 - 25.32 - 25.80 - 25.52

	Dutch youth male swimmers on track to reach the elite level						
	13	**14**	**15**	**16**	**17**	**18**	**19**
Mean swim performance (%WR)	123.1 ± 2.2	119.5 ± 2.4	115.2 ± 1.7		107.6 ± 2.3	106.6 ± 2.0	105.6 ± 2.6
Start (%)					106.7 ± 4.5	105.1 ± 4.2	102.0 ± 4.7
Turn (%)					99.6 ± 2.5	98.7 ± 2.3	97.2 ± 3.0
Maximal swimming velocity (%)	95.2 ± 3.7	97.6 ± 3.1	99.0 ± 2.9		100.7 ± 1.9	101.0 ± 1.8	101.6 ± 2.6
Stroke index (%)	77.9 ± 6.4	82.6 ± 7.1	89.8 ± 6.7		83.5 ± 8.6	84.2 ± 8.5	89.1 ± 4.4
Lower body power (cm)	51.1 ± 2.0	52.5 ± 2.0	54.4 ± 2.4				
Lower body power (W/kg)					41.0 ± 4.2	42.5 ± 2.8	45.4 ± 2.8
Height (cm)	175.4 ± 9.2	180.6 ± 9.0	186.9 ± 3.7		188.1 ± 8.0		
Self-regulation of learning (reflection processes)				3.6 ± 0.6			
Age of Peak Height Velocity (years)		13.1 ± 0.4					
Swim training (hours per week)	9.8 ± 2.3	11.7 ± 2.6	11.6 ± 3.0		14.7 ± 2.7		

Note. Reference values derived from established, international senior elite swimmers pertain to the 100m Freestyle event, unless otherwise indicated, while those obtained from Dutch youth swimmers on track to reach the elite level cover various events. Swim performance is indicated as the season best time relative to the prevailing World Record (WR). Within season progression is indicated as the percentage change a swimmer has moved towards the prevailing WR.

Appendix B. Reference values for the athletic profile of female swimmers on track to reach the elite level, categorized by age.

	Established, international senior elite female swimmers						
	12	**13**	**14**	**15**	**16**	**17**	**18**
Minimal level of swim performance (%WR)	129.1	121.3	117.5	115.1	113.9	112.6	111.9
Mean swim performance (%WR)	115.7 ± 2.1	111.4 ± 1.5	109.0 ± 1.2	107.6 ± 1.1	107.0 ± 1.1	106.5 ± 1.0	106.3 ± 1.0
Within season progression (%)	16.9 ± 4.1	20.9 ± 4.9	21.6 ± 5.5	23.8 ± 3.9	22.8 ± 3.8	23.0 ± 3.4	24.8 ± 3.3
Pacing behavior (50-100m %)	48.28 - 51.72	48.28 - 51.72	48.29 - 51.71	48.29 - 51.71	48.30 - 51.70	48.30 - 51.70	48.30 - 51.70
Pacing behavior (50-100-150-200m %)	23.23 - 25.44 - 25.97 - 25.36	23.27 - 25.45 - 25.93 - 25.35	23.30 - 25.42 - 25.90 - 25.38	23.32 - 25.40 - 25.87 - 25.41	23.35 - 25.37 - 25.84 - 25.44	23.37 - 25.35 - 25.81 - 25.47	23.40 - 25.33 - 25.78 - 25.49

	Dutch youth female swimmers on track to reach the elite level						
	12	**13**	**14**	**15**	**16**	**17**	**18**
Mean swim performance (%WR)	122.3 ± 2.5	119.1 ± 2.6	115.6 ± 1.9		109.0 ± 1.0	108.6 ± 0.9	108.4 ± 0.8
Start (%)					110.0 ± 5.3	108.7 ± 5.5	106.8 ± 5.3
Turn (%)					100.5 ± 4.1	99.5 ± 4.4	99.2 ± 4.9
Maximal swimming velocity (%)	95.6 ± 3.4	96.1 ± 2.7	98.5 ± 2.6		100.8 ± 3.0	101.2 ± 3.1	100.8 ± 3.1
Stroke index (%)	82.7 ± 4.3	82.7 ± 4.5	86.1 ± 5.4		93.5 ± 3.7	94.2 ± 3.8	94.3 ± 4.3
Lower body power (cm)	42.7 ± 5.0	44.6 ± 4.9	46.5 ± 3.6				
Lower body power (W/kg)					32.2 ± 3.6	32.4 ± 4.3	35.1 ± 6.2
Height (cm)	167.8 ± 7.3	171.2 ± 5.7	174.0 ± 3.2		177.4 ± 7.2		
Self-regulation of learning (reflection processes)				3.6 ± 0.6			
Age of Peak Height Velocity (years)		11.5 ± 0.3					
Swim training (hours per week)	7.8 ± 1.4	9.3 ± 1.4	11.1 ± 3.0		16.0 ± 2.6		

Note. Reference values derived from established, international senior elite swimmers pertain to the 100m Freestyle event, unless otherwise indicated, while those obtained from Dutch youth swimmers on track to reach the elite level cover various events. Swim performance is indicated as the season best time relative to the prevailing World Record (WR). Within season progression is indicated as the percentage change a swimmer has moved towards the prevailing WR.

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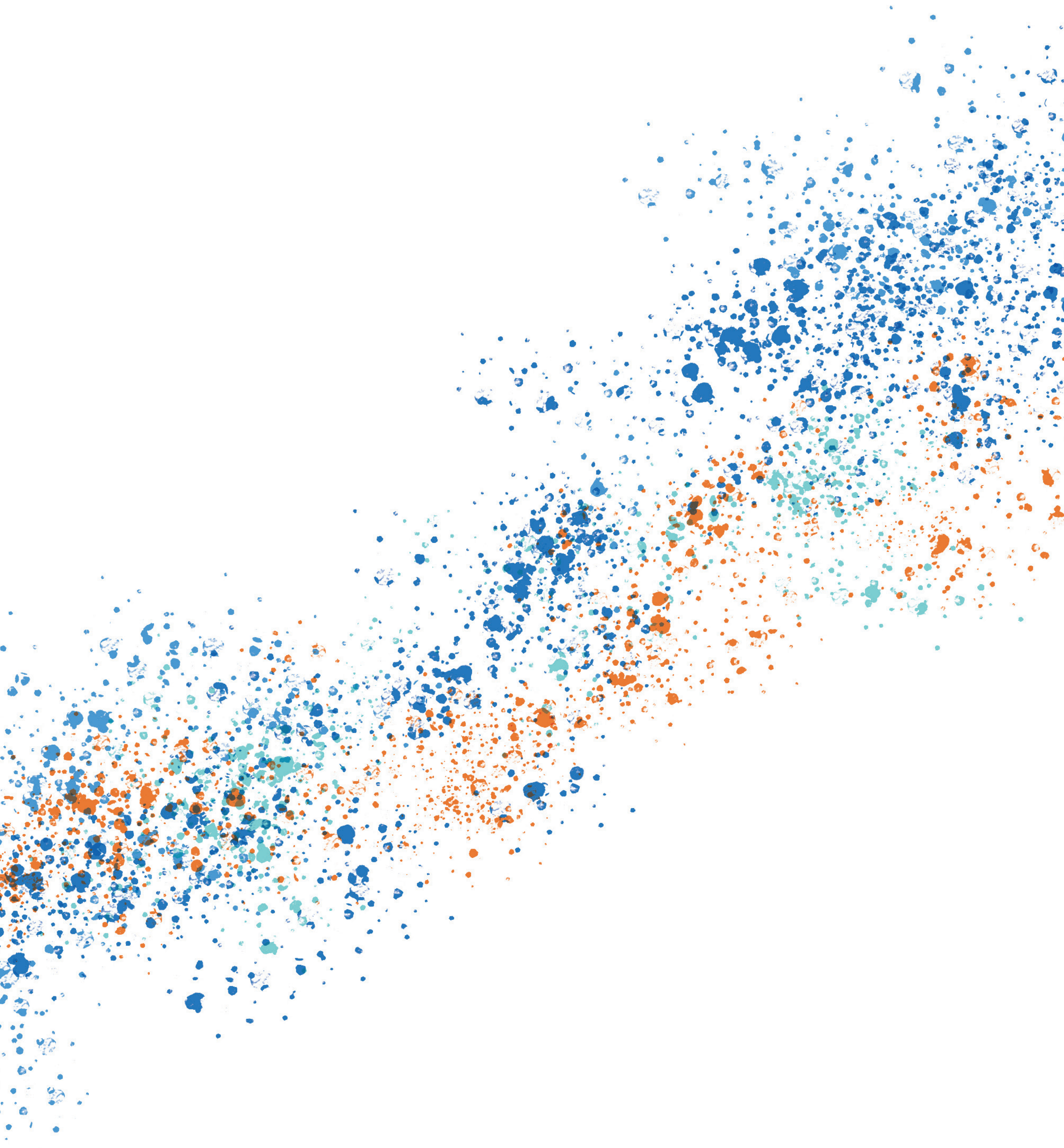

Appendices

Summary

Competitive swimming has a long history of success in The Netherlands, featuring Olympic Champions such as Pieter van den Hoogenband and Ranomi Kromowidjojo. Along their journey to the podium, they outperformed many peers, a challenge the aspiring new wave of swimmers must also overcome to achieve greatness. But what distinguishes those who reach the top from those who don't? Answering this question is crucial for effectively guiding swimmers towards the elite level and maintaining the nation's competitiveness. Therefore, this thesis examines the pathway to swimming expertise, offering both scientific and practical insights to identify and nurture swimming talent.

Identifying the fastest swimmer within an age group is straightforward, but predicting who among them will emerge as the next elite swimmer is far more challenging. **Chapter 1** delves into these complexities of talent identification and development, and discusses how scientific research can provide valuable insights in this area. Longitudinal and multidimensional studies that track swimmers' development across various domains over time are crucial in this regard. Therefore, this thesis examines both swim performance as well as the underlying physical, mental, technical and tactical characteristics of swimmers on track to reach the elite level (best 50 world-wide). Using various statistical methods, including analysis of variance and multilevel analyses, their development is compared to their peers who, while off track, still attained success at the national level (best 50 nationally). Through six studies, this thesis unravels the key characteristics and developmental patterns that relate to international swimming success.

The world's best swimmers are incredibly fast, but were they already this exceptional at a younger age? **Chapter 2** answers this question by retrospectively analyzing the development in swim performance of 3.146 swimmers who achieved varying levels of success in adulthood, ranging from high-competitive (top 50 nationally), sub-elite (top 8 nationally), elite (top 50 worldwide) to top-elite (top 8 worldwide). This study mapped out their developmental trajectory in season best times from the age of 12 onwards. Swimmers who eventually reached the top-elite level outperformed their peers who ended at the high-competitive level from the age of 12. By the age of 14, they were also faster than the later sub-elite swimmers. While top-elite females surpassed their sub-elite and elite counterparts at the same age, top-elite males did not outperform the later elite swimmers until the age of 18. The age at which top-elite swimmers reached the top 8 worldwide varied widely. This demonstrates that within the higher performance standards of top-elite swimmers during their teenage years, there were many pathways leading to their swimming success.

While Chapter 2 focused on the development of season best times over multiple years, **Chapter 3** investigates whether swimmers who reached the elite level improved more within a season compared to peers who 'merely' achieved the high-competitive level. Although their performance level in adulthood varied, all 3,199 swimmers in this study

were considered on track to reach the elite level during their junior years. This assessment was based on international performance benchmarks derived from Chapter 2, which establish the minimum swimming times needed per age group according to historical data to reach the elite level. These benchmarks will be used consistently throughout the thesis to categorize junior swimmers as either on track or not on track. Swimmers who eventually reached the elite level demonstrated greater improvement between their first swim performance of the season and their season best time, starting from age 13 (females) and 15 (males). However, elite swimmers did not show any difference compared to high-competitive swimmers in the period between their previous season best time and the first swim performance of the season. During this period, swimmers of both groups experienced an average decline of ~1% in their swim performance.

Chapter 4 narrows down the analysis of swim times to within a single race, examining the development of pacing behaviour of 5,818 swimmers who reached the elite, sub-elite and high-competitive level in adulthood. Elite males in the 100m freestyle developed a relatively faster first 50m from the age of 17, indicative of a more all-out approach compared to later high-competitive swimmers. No such effects were found for female swimmers. In the 200m freestyle, both male and female elites exhibited more even pacing behavior from age 16 (males) and age 13 (females) onwards compared to high-competitive swimmers. This highlights that elite swimmers during their junior years demonstrate pacing behavior which better fits the task demands, mirroring that of adult elite swimmers.

To be and remain on track towards elite status requires not only extensive training hours but also quality of training. Self-regulation of learning is proposed to be crucial in this process. As such, **Chapter 5** examines whether swimmers who are on track to reach the elite level apply self-regulation of learning (SRL) subprocesses more frequently in their daily training sessions compared with swimmers who are not on this track. Swimmers on track to the elite level were characterized with higher scores on reflection processes, but relatively lower scores in effort during training. Those on track who were improving more within a season were engaged in more frequent evaluation after training. These findings suggest that swimmers on track may learn and train more effectively and efficiently. Ultimately, this proactive involvement could contribute to a higher quality of daily training, which may result in greater improvements during a season, higher performance levels, and a greater chance of reaching the elite level.

In **Chapter 6**, 29 Dutch talented swimmers were followed during their transition to the senior level. This transition is regarded as the most demanding and challenging phase on the path to swimming excellence. Over a period of four seasons, data were collected on their development in terms of season best times and underlying characteristics such as their maximal swimming velocity, stroke index (an indirect measure of swimming efficiency), starts, turns and lower body power. Swimmers who were on track towards the elite level at early senior age (males aged 18-19 years, females aged 17-18 years) were already on track at the end of their junior years. At this age (males aged 17, females aged 16), they also had faster season best times and demonstrated a higher level on most underlying characteristics compared to those who were no longer on track towards the elite level as early seniors. Furthermore, swimmers on track towards the elite level distinguished themselves by their ongoing progress during the junior-to-senior transition. Males showed greater advancements in their season best times, maximal swimming velocity, and turns, while females, in addition to improving their season best times, also became more efficient swimmers. This highlights that swimmers on track towards the elite level maintain and even extend their advantage by the end of their junior years and throughout the transition to seniors.

Chapter 7 closely mirrors the study in Chapter 6 but focuses on a younger group of swimmers, investigating the development of 90 Dutch swimming talents during the pubertal years. The swimmers were between 13-15 years old (males) and 12-14 years old (females) when they were followed for three seasons on their season best times and underlying characteristics such as their maximal swimming speed, stroke index, and lower body power. Despite the difference in developmental phases between the studies, the findings revealed a similar pattern as in Chapter 6. Swimmers who were on track to the elite level after puberty (males aged 16; females aged 15) were already on track during the pubertal years. Additionally, during their teenage years, they had faster season best times and had a higher maximal swimming velocity than those who were not on track. Males on track also swam more efficiently, while females were characterized by greater lower body power and taller stature. Furthermore, those who remained on track after puberty made more progress during the pubertal years in their season best times, maximal swimming velocity, and stroke index (exclusively for males) compared to peers who where not on track.

In **Chapter 8,** the findings of the six studies in this thesis are presented into two athletic profiles - one for males and one for females. Across various ages, these athletic profiles highlight the key characteristics that differentiate swimmers on track towards the elite level from those who are not. In essence, the findings demonstrate that swimmers who reached higher levels of swim performance later in their career consistently outperformed their lower-level peers from the age of 12 onwards. Achieving season best times within the age-related international performance benchmarks appear to be a prerequisite for advancing to the elite level, yet these early achievements in itself do not necessarily guarantee success. This is evidenced by the fact that while most Dutch swimming talents were on track towards the elite level at the beginning of their teenage years, only a few maintained this trajectory as their careers progressed. Swimmers who sustained this level showed greater improvement in their swim times across and within seasons. Additionally, they demonstrated higher levels and greater progress in a multidimensional profile of underlying physical, mental, technical, and tactical characteristics. The key characteristics in which they excelled compared to swimmers off track varied across developmental phases and between males and females.

Overall, this thesis provides a nuanced, fine-grained, and concrete understanding of the pathway to international swimming success. It underscores that swimmers on track towards the elite level are characterized by high levels and significant progress in both season best times and underlying characteristics throughout their careers. These findings refute a one-dimensional approach to talent identification and development and emphasize the importance of continuously monitoring, guiding, and evaluating swimmers across performance, physical, mental, technical, and tactical aspects. Whereas youth swimmers previously could only be compared with themselves or immediate peers, this thesis offers age-specific profiles and developmental patterns of swimmers on track towards the elite level. Coaches can use these objective data and evidence-based insights to better assess the potential of their swimmers and guide them optimally towards success. As such, this thesis demonstrates the value of multidimensional and longitudinal research for the field of (elite) sports practice.

Nederlandse samenvatting

Nederland kent een rijke geschiedenis vol zwemsucces met onder andere Olympisch kampioenen zoals Pieter van den Hoogenband en Ranomi Kromowidjojo. Op hun weg naar het podium hebben zij vele leeftijdsgenoten achter zich gelaten, een uitdaging die ook de nieuwe generatie zwemmers met grote dromen zal moeten aangaan. Maar wat maakt dat de ene zwemmer de top haalt en de andere niet? Het beantwoorden van die vraag is belangrijk om zwemmers optimaal te begeleiden naar het hoogste niveau en om ook in de toekomst als zwemland goed te blijven presteren. Dit proefschrift onderzoekt daarom de weg naar de zwemtop en biedt zowel wetenschappelijke als praktische inzichten om zwemtalent te herkennen en ontwikkelen.

Hoewel het makkelijk is om de snelste zwemmer binnen een leeftijdsgroep aan te wijzen, is het veel moeilijker om in te schatten wie van hen zich zal ontwikkelen tot een toekomstige topper. In **Hoofdstuk 1** worden deze en andere uitdagingen in talentherkenning en -ontwikkeling verder besproken, evenals hoe wetenschappelijke studies hierbij kunnen helpen. Vooral longitudinaal en multidimensionaal onderzoek dat zich richt op het in kaart brengen van de ontwikkeling van zwemmers op meerdere vlakken, kan veel betekenen. In dit proefschrift worden daarom niet alleen zwemtijden, maar ook onderliggende fysieke, mentale, technische en tactische kwaliteiten bestudeerd van zwemmers die op koers zijn naar het elite niveau (top 50 wereldwijd). Met behulp van verschillende statistische methoden, waaronder variantieanalyse en multilevelanalyse, wordt hun ontwikkeling vergeleken met die van leeftijdsgenoten die enkel nationaal succesvol zijn (top 50 nationaal). De zes studies in dit proefschrift ontrafelen daarmee de kenmerken en ontwikkelingspatronen die samenhangen met internationaal zwemsucces.

Dat de beste zwemmers wereldwijd hard kunnen zwemmen, is duidelijk, maar deden zij dat ook al toen ze jonger waren? Tot het onderzoek zoals beschreven in **Hoofdstuk 2** was het antwoord op die vraag onbekend. Door de ontwikkeling in seizoensbeste tijden van 3.146 zwemmers te analyseren, is daar verandering in gekomen. Deze zwemmers bereikten op volwassen leeftijd verschillende niveaus van succes, oplopend van zeer-competitief (top 50 nationaal), sub-elite (top 8 nationaal), elite (top 50 wereldwijd) naar top-elite (top 8 wereldwijd) niveau. Aan de hand van hun geschiedenis aan zwemtijden is in kaart gebracht hoe de zwemmers zich vanaf hun jeugdjaren hebben ontwikkeld. Zwemmers die uiteindelijk het top-elite niveau bereikten, zwommen vanaf 12 jaar sneller dan hun leeftijdsgenoten die op het zeer-competitieve niveau eindigden. Vanaf 14 jaar presteerden zij ook beter dan de latere sub-elite zwemmers. Waar top-elite vrouwen hun sub-elite en elite tegenhangers op dezelfde leeftijd voorbijstreefden, waren top-elite mannen pas vanaf 18-jarige leeftijd sneller dan de latere elite zwemmers. De leeftijd waarop top-elite zwemmers uiteindelijk doorbraken tot de wereldwijde top 8 varieerde sterk. Dit laat zien dat top-elite zwemmers al op jonge leeftijd beter presteerden dan leeftijdsgenoten die op lagere niveaus eindigden, en dat er vanuit dat hoge niveau verschillende wegen naar hun zwemsucces leidden.

Waar Hoofdstuk 2 de ontwikkeling van seizoensbeste tijden over meerdere jaren belicht, onderzoekt **Hoofdstuk 3** of zwemmers die het elite niveau bereikten zich sneller ontwikkelen binnen één seizoen ten opzichte van degenen die 'slechts' het zeer-competitieve niveau behaalden. Hoewel hun eindniveau op volwassen leeftijd verschillend was, lagen alle 3.199 zwemmers binnen deze studie tijdens hun jeugd op koers voor het bereiken van het elite niveau. Of zwemmers op koers lagen, is bepaald aan de hand van internationale prestatie benchmarks die voortkomen uit Hoofdstuk 2. Per leeftijdscategorie tonen deze benchmarks de zwemtijd die volgens historische data minimaal nodig lijkt om uiteindelijk het elite niveau te bereiken. Ook in het vervolg van dit proefschrift worden deze benchmarks gebruikt om jeugdzwemmers in te delen als zijnde op koers of niet op koers naar het elite niveau. Vanaf hun tienerjaren (mannen op 15-jarige leeftijd; vrouwen op 13-jarige leeftijd) boekten zwemmers die uiteindelijk het elite niveau bereikten meer vooruitgang in de periode tussen hun eerste zwemtijd van het seizoen en hun seizoensbeste tijd. Elite zwemmers verschilden niet van de zeer-competitieve zwemmers in de periode tussen hun vorige seizoensbeste tijd en de eerste zwemtijd van het seizoen. In deze periode gingen zwemmers uit beide groepen gemiddeld ~1% achteruit in hun zwemprestaties.

Hoofdstuk 4 brengt de analyse van zwemtijden terug tot één enkele race, en richt zich op de ontwikkeling van pacing gedrag onder 5.818 zwemmers die op volwassen leeftijd het elite, sub-elite en zeer-competitieve niveau behaalden. Op de 100 meter vrije slag zwommen elite mannen vanaf 17 jaar hun race volgens een meer "all-out" strategie dan de latere zeer-competitieve zwemmers. Bij vrouwen werden geen groepsverschillen gevonden op deze afstand. Op de 200 meter vrije slag toonden zowel elite mannen (vanaf 16 jaar) als vrouwen (vanaf 13 jaar) een meer gelijkmatige verdeling van hun race in vergelijking met de latere zeer-competitieve zwemmers. Daarmee laten elite zwemmers gedurende hun tienerjaren in vergelijking met zeer-competitieve zwemmers pacing gedrag zien dat beter past bij de taak en overeenkomt met dat van volwassen elite zwemmers.

Om op weg te zijn en te blijven naar de top moeten zwemmers niet alleen veel maar ook slim trainen. Zelfregulatie wordt verondersteld hier een belangrijke rol in te spelen. **Hoofdstuk 5** onderzoekt daarom het gebruik van zelf-regulatieve vaardigheden voor, tijdens en na de training onder 157 Nederlandse zwemtalenten. Zwemmers op koers naar het elite niveau gaven aan vaker tijdens de training te reflecteren in vergelijking met leeftijdsgenoten die niet op koers lagen, maar scoorden zichzelf relatief lager op inzet. Binnen het groepje zwemmers op koers naar het elite niveau scoorden degenen die meer vooruitgang boekten in het seizoen hoger op het evalueren na de training. Het lijkt daarmee dat talentvolle zwemmers op koers naar het elite niveau effectiever en efficiënter trainen. Dit zou uiteindelijk kunnen leiden tot een hogere dagelijkse kwaliteit van trainen, wat kan resulteren in meer vooruitgang in een seizoen, hogere prestatieniveaus en een grotere kans om de top te bereiken.

In **Hoofdstuk 6** zijn 29 Nederlandse zwemtalenten gevolgd in de periode dat zij de overstap maakten naar de senioren. Deze transitie wordt gezien als de meest veeleisende en moeilijke fase in de weg naar de zwemtop. Over een periode van vier seizoenen werden gegevens verzameld over hun ontwikkeling op het gebied van zwemtijden en onderliggende kwaliteiten zoals hun topsnelheid, stroke index (een indirecte maat voor zwemefficiëntie), starttijd, keerpunttijd en power in het onderlichaam. Zwemmers die als beginnende senioren (mannen van 18-19 jaar, vrouwen van 17-18 jaar) op koers lagen naar het elite niveau, lagen ook al op koers aan het einde van hun jeugdjaren. Op deze leeftijd (mannen van 17 jaar; vrouwen van 16 jaar) zwommen ze snellere seizoensbeste tijden en lieten ze een hoger niveau zien op de meeste onderliggende kwaliteiten dan degenen die op seniorenleeftijd niet meer op koers naar het elite niveau lagen. Daarnaast kenmerkten de zwemmers op koers naar het elite niveau zich door zich (meer) te blijven ontwikkelen gedurende de overstap naar de senioren. De mannen maakten meer progressie op hun seizoensbeste tijden, topsnelheid en keerpunttijden, terwijl de vrouwen, naast hun voortgang in seizoensbeste tijden, ook steeds efficiënter gingen zwemmen. Dit laat zien dat zwemmers op koers naar het elite niveau hun voorsprong aan het einde van de jeugdjaren vasthouden en zelfs uitbouwen gedurende de overstap naar de senioren.

Hoofdstuk 7 gaat ten opzichte van Hoofdstuk 6 een stapje terug in de tijd en onderzoekt de ontwikkeling van 90 Nederlandse zwemtalenten tijdens de puberjaren. De zwemmers waren tussen de 13-15 jaar (mannen) en 12-14 jaar (vrouwen) toen zij gedurende drie seizoenen werden gevolgd op hun zwemtijden en onderliggende kwaliteiten zoals hun topsnelheid, stroke index en power in het onderlichaam. Zwemmers die na de puberteit (mannen van 16 jaar; vrouwen van 15 jaar) op koers lagen naar het elite niveau, lagen dat ook al gedurende hun puberjaren. Daarnaast zwommen ze tijdens hun puberjaren snellere seizoensbeste tijden en hadden ze een hogere topsnelheid dan degenen die niet op koers lagen. Mannen op koers naar het elite niveau zwommen daarnaast ook efficiënter, terwijl vrouwen zich kenmerkten door meer power in het onderlichaam en een grotere lichaamslengte. Daarnaast maakten de zwemmers die na de puberteit op koers lagen naar het elite niveau meer progressie gedurende hun puberjaren op hun seizoensbeste tijden, topsnelheid en stroke index (enkel voor mannen) dan degenen die niet op koers lagen.

In **Hoofdstuk 8** worden de resultaten van de zes studies in dit proefschrift samengebracht in twee profielen, één voor mannen en één voor vrouwen. Deze profielen laten over verschillende leeftijden zien wat zwemmers op koers naar het elite niveau kenmerkt ten opzichte van degenen die dat niet liggen. Samenvattend tonen de bevindingen aan dat zwemmers die verder in hun carrière zijn gekomen, vanaf 12 jaar al beter presteerden dan leeftijdsgenoten die uiteindelijk een lager niveau bereikten. Het neerzetten van een seizoensbeste tijd die binnen de leeftijdsgebonden internationale prestatie benchmark valt, lijkt een voorwaarde om verder te kunnen groeien naar het elite niveau, maar biedt tegelijkertijd geen garantie. Dit blijkt uit het feit dat hoewel de meeste Nederlandse zwemtalenten aan het begin van hun tienerjaren op koers lagen naar het elite niveau, slechts enkelen dat ook bleven naarmate hun carrière vorderde. Zwemmers die dit niveau wisten te handhaven, boekten meer vooruitgang in hun zwemtijden tussen en binnen seizoenen. Daarnaast lieten zij op een veelzijdig profiel van onderliggende fysieke, mentale, technische en tactische kwaliteiten een hoger niveau en meer progressie zien. De specifieke kwaliteiten waarin zij beter waren ten opzichte van zwemmers die niet op koers lagen, verschilden per ontwikkelingsfase en geslacht.

Al met al biedt dit proefschrift een genuanceerd, verfijnd en concreter begrip van de weg naar internationaal zwemsucces. Het benadrukt dat zwemmers op koers naar het elite niveau zich kenmerken door de combinatie van hoge niveaus en sterke vooruitgang op zowel seizoensbeste tijden als onderliggende kwaliteiten gedurende hun carrière. Deze bevindingen laten geen ruimte voor een eendimensionale aanpak binnen talentherkenning en -ontwikkeling, en onderstrepen het belang om zwemmers te volgen, begeleiden en evalueren op zowel prestatieve, als fysieke, mentale, technische en tactische aspecten. Waar voorheen jeugdzwemmers enkel konden worden vergeleken met zichzelf of directe leeftijdsgenoten, voorziet dit proefschrift in leeftijdsgebonden profielen en ontwikkelingspatronen van zwemmers op koers naar het elite niveau. Coaches kunnen deze objectieve gegevens en op bewijs gebaseerde inzichten gebruiken om de potentie van hun zwemmers beter in te schatten en hen optimaal te begeleiden op hun weg naar succes. Daarmee toont dit proefschrift de waarde van longitudinaal en multidimensionaal onderzoek voor de (top)sportpraktijk.

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Marije, of het nu bellend was (wat hebben we dat veel gedaan hè gedurende corona?!) of op de faculteit, ons vaste overleg op maandag 11 uur was eigenlijk standaard te kort.

Hoe kan het ook anders als het niet alleen over onderzoek ging, maar ook over het werken met talentvolle sporters en het vinden van balans op allerlei vlakken. Als ik twijfelde en verdwaalde in alle mogelijkheden, haalde jouw helikopterview mij uit de knoop. Zonder antwoorden op te leggen, gaf je richting waardoor de volgende stap ineens weer zichtbaar was, en gemaakte keuzes eigen voelden. Je gaf me vertrouwen en bevestiging als ik dat nodig had, maar hebt me ook aangemoedigd om dingen te doen die ik toch soms liever uit de weg wilde gaan, zoals presenteren, college geven, en naar een wetenschappelijk congres gaan. En hoewel ik daar op het moment zelf niet om stond te springen, was dat eigenlijk… natuurlijk heel goed. Door jou zie ik mijn eigen kwaliteiten (steeds) beter in, laat ik de boel ook wel eens de boel, en begrijp ik steeds meer van de subtiele nuances in talentontwikkeling. Dankjewel voor alles en ik hoop nog veel van je te mogen leren!

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Collega's van het InnoSportLab de Tongelreep en de KNZB, het was fantastisch om met jullie te werken! De combinatie van jullie gedrevenheid, creativiteit, interesse, en humor maakten de Tongelreep echt de allerleukste werkplek.

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Carlo, dat jij hier nog even in de spotlight word gezet, zou niet als een verrassing moeten komen. Er is heel weinig wat jij niet wist te regelen rondom de testmomenten. Of het nu een camera met kuren was of een tekort aan testleiders, ik kon altijd op jou rekenen. Je hebt je ingezet voor dit onderzoek alsof jij zelf de promovendus was en dat vind ik heel bijzonder! Daarbij hield je me geregeld uit de wind als de emmer qua werkzaamheden bij het lab weer tot het randje vol liep, zodat ik mij kon focussen op het onderzoek. Mijn balans daarin houden was een voortdurende uitdaging, maar jij hielp dat goed te bewaken. Bedankt voor alles en ik blijf erbij: iedereen zou een Carlo moeten hebben!

Sander, hoe hadden we ooit alles kunnen meten en analyseren zonder jouw innovaties? Ik blijf het indrukwekkend vinden wat jij allemaal kan programmeren en ben heel benieuwd wat dit de zwemsport nog meer gaat brengen. Jouw scherpe kijk heeft me veel geleerd, en je bent absoluut een inspiratie geweest voor mijn ontwikkeling op de meer technische aspecten van zwemmen en onderzoek.

Roald, zonder jouw ambitie, visie en toewijding om met wetenschap en innovatie het Nederlands zwemmen naar een hoger niveau te tillen, was deze PhD er niet geweest. Het was namelijk niet de vraag óf het lab op meerdere domeinen promotieonderzoek zouden gaan doen, maar wanneer. Hoewel de plannen rondom het onderzoek naar talentontwikkeling nog niet rond waren, gaf je mij op voorhand de kans om als embedded scientist aan te sluiten bij het lab en daar heb ik heel veel aan te danken! Jij laat zien dat je vaak gewoon moet beginnen voordat je er 100% klaar voor bent, en dat zolang je niet opgeeft en creatief bent, er altijd een weg is. Dat ga ik niet vergeten. Het was een eer om de eerste promovenda op het gebied van talentontwikkeling te zijn binnen het lab, en ik hoop dat er nog vele zullen volgen. Dankjewel!

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Marcel, Patrick, Kees, Henri, Geert, Jeroen en Job, ik heb veel gehad aan onze gesprekken en discussies, waarvan de spontane meetings langs de badrand vaak de beste inzichten met zich mee brachten. Daardoor heb ik veel geleerd over de complexiteit van talentontwikkeling en de verschillende wegen naar het topzwemmen, plus wat dat betekent voor een coach. Jullie openheid, nieuwsgierigheid en kritische blik motiveerden mij altijd om weer een stapje verder te denken!

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About the author

Aylin Kim Post was born on September 13th 1992 in Harderwijk, The Netherlands. After completing her secondary education in 2010, she enrolled at the University of Groningen to pursue her studies in Human Movement Sciences. Driven to make a meaningful contribution to the field of elite sports, she specialized in sport sciences during her master's program. However, thirst for adventure led her to briefly venture into a healthy aging project during her internship in Adelaide, Australia, from August 2015 to May 2016. During her time there, she investigated the effects of non-invasive brain stimulation protocols on primary motor cortex neuroplasticity in both young and older adults, leading to her first publication as a (shared) first author (Opie et al., 2017).

In August 2016, upon her return to Groningen, The Netherlands, Aylin was presented with the opportunity to gain practical experience as a junior embedded scientist at Sportcentrum Papendal in Arnhem. In this position, she had the privilege of working with elite athletes across various sports, ranging from cycling to volleyball.

In March 2017, Aylin began her role as an embedded scientist in swimming for the KNZB and InnoSportLab de Tongelreep. A year and a half later, she embarked on her PhD journey, which was funded through a unique collaboration between the University Medical Centre Groningen, University of Groningen, the KNZB and InnoSportLab de Tongelreep. Throughout her PhD, Aylin successfully balanced her research responsibilities with her role as an embedded scientist. In 2020, she launched Talent Topics, an online platform, to make the science behind talent identification and development accessible to practitioners. In 2022, Aylin won the Top Publication Awards from the research institute SHARE for her journal publication studying the development of pacing behavior in talented swimmers.

Presently, Aylin has embarked on a new chapter in her career as Specialist Talent Development in Volleyball. Drawing upon the knowledge and experience gained from her years of research and practical involvement, she aspires to make a tangible impact in the field, furthering her commitment to advancing talent identification and development systems in elite sports.

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