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Thinking outside the box: comparing age at performance milestones of swimmers to cross-country skiers and biathletes

Malin Jonsson Kårström [a], Jesús J. Ruiz-Navarro [b,c], Michael Romann [d,e], Dennis-Peter Born [d,e,f,*]

[a] Swedish Winter Sports Research Centre, Department of Health Sciences, Mid Sweden University, Sweden
[b] Aquatics Lab, Department of Physical Education and Sports, Faculty of Sport Sciences, University of Granada, Spain
[c] Human Performance and Sports Science Laboratory, Faculty of Sport Sciences, University of Murcia, Spain
[d] Department for Elite Sport, Swiss Federal Institute of Sport Magglingen, Switzerland
[e] Faculty of Science and Medicine, University of Fribourg, Switzerland
[f] Swiss Development Hub for Strength and Conditioning in Swimming, Swiss Aquatics – National Swimming Federation, Switzerland

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ABSTRACT

Objectives: To compare age at key performance milestones between technical whole-body endurance sports and performance levels.
Design: Longitudinal big data analysis.
Methods: All top 30 swimmers, cross-country (XC) skiers and biathletes, who competed at the latest World championships (WC) were included and their ages at specific performance milestones (debut, first 17–30 rank, 9–16 rank, top 8) at junior (JWC) and adult WC were extracted from databases (719 women and 850 men). Athletes were divided into various performance levels based on their best individual ranking from adult competitions and compared using linear mixed model analysis.
Results: Only ~40% of the WC swimmers had competed in the JWC compared to ~90% of XC skiers and biathletes. Swimmers were, on average, 2 and 4 years younger at JWC and WC, respectively, than XC skiers and biathletes. In all three sports, there was an age gap ($p < 0.05$) between the highest junior performance milestone and adult WC debut (3–4 years) but no age difference ($p > 0.05$) between the performance milestones or performance levels at JWC. On average, female swimmers reached performance milestones one year earlier than their male counterparts, while there was no sex difference in XC skiing and biathlon.
Conclusions: The present findings encourage reassessment of sport-specific stereotypes regarding long-term athlete development. Although overall development patterns are similar between men and women, sex-specific training and competition planning is necessary at key junior career stages. Analyzing key structural elements of development systems across three technical whole-body endurance sports provides insights to develop future strategies for long-term athlete development.
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Practical implications

- Analyzing the key structural elements of development systems across three technical whole-body endurance sports provides insights to inform future strategies for long-term athlete development.
- Talent development systems in swimming should consider appropriate performance progression and junior eligibility alongside specific intermediate competitions.
- Although overall development patterns are similar between men and women, sex-specific training and competition planning is necessary at key junior career stages.

1. Introduction

Swimmers exhibit an earlier peak performance age than athletes in other technical whole-body endurance sports. While swimmers begin to peak perform as young as 21 years of age across the various race distances,[1] cross-country (XC) skiers, for example, begin to peak aged 26 years in both sprint and distance events.[2] This earlier peak in swimming is accompanied by an earlier performance plateau[1,3] and relatively short window of approximately 2–3 years to compete at the highest

Abbreviations: XC, cross-country; FIS, International Skiing Federation; IBU, International Biathlon Union; WC, World championships; JWC, junior World championships.

* Corresponding author.
E-mail address: dennis.born@swiss-aquatics.ch (D.-P. Born).
Social media: @EHSM_Magglingen (D.-P. Born).

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level.[1] While swimmers typically conclude their competitive careers by the end of their 20s,[1] elite XC skiers continue to improve performance for a longer period, enabling them to compete successfully well into their 30s.[2]

The early end of swimming careers is surprising, as it is a non-impact, non-weight-bearing sport with a relatively low injury rate and would therefore be expected to permit longer athletic careers.[4] Given the lack of clear physiological explanations for why swimmers would retire earlier than other whole-body endurance athletes, i.e. XC skiers and biathletes, psychological factors may play an important role in the earlier end of swimming careers. The repetitive nature of swimming training and competition (involving an infinite number of laps in 25 or 50 m pools) is associated with a "lack of enjoyment" and "getting bored", which are frequently named reasons for swimmers to end their competitive careers.[5] These feelings may be further exacerbated by early introduction of structured training and competition programs, which swimmers typically enter at 11–12 years of age or earlier[6] in order to accumulate the required training volume before reaching peak performance age.[7]

This raises the question of whether swimmers begin to peak as early as 21 years of age due to inherent sport-specific demands,[1] or whether this pattern is largely driven by the structure of swimming's development and competition system. Given the present circumstances, this system necessitates an early onset of structured training, which continues to favor biologically early-maturing athletes and those born earlier in the selection year.[8] Comparing swimming with other technical whole-body endurance sports may therefore help challenge traditional assumptions and provide novel insights for the design of more effective long-term athlete development programs in swimming.

Similar to swimming, XC skiing and biathlon are endurance sports that require a high degree of technical proficiency to effectively translate physiological capacity into propulsion.[9,10] In swimming, athletes must "catch" the water and progressively build resistance throughout the underwater arm stroke to generate optimal hydrodynamic lift, while precisely coordinating shoulder and hip rotations with minimal alterations in joint angles substantially affecting movement efficiency.[11,12] Likewise, XC skiers must carefully time and modulate force application during leg and upper-body push-off to maximize propulsion while minimizing pole subsidence and ski slippage, particularly under soft or icy snow conditions.[10,13]

In addition to propulsion mechanics, all three sports require seamless transitions between distinct technical phases. Swimmers must efficiently transition between full-stroke swimming, wall approach, turning and underwater phases,[14] whereas XC skiers and biathletes transition continuously between uphill, downhill, flat terrain and turns.[15] Biathlon introduces an additional acyclic technical component in the form of rifle shooting, which demands precise timing, postural control, and mental focus and has a substantial impact on competitive performance similar to turning phases in swimming.[14,16,17]

Despite the similarities between swimming, XC skiing and biathlon, there are marked differences in peak performance age and career trajectories. Therefore, the aim of this study was to compare the age at key performance milestones between these three technical whole-body endurance sports. The hypothesis was that elite female and male swimmers reach the various performance milestones, i.e. debut, first 17–30 rank, 9–16 rank and top 8, earlier than XC skiers and biathletes during both junior and senior WC.

2. Methods

All top 30 athletes from individual events of the latest long-course (50 m pool length) World championships (WC) in swimming (2019, 2022, 2023), XC skiing (2019, 2021, 2023) and biathlon (2021, 2023, 2024) were included in the study. The data from the 2024 Doha swimming WC were excluded from the analysis, as it took place in February of the Olympic year. Due to the unusual time point, many favorites did not attend the championships or only used it as a preparatory competition for the Olympic Games. In total, 1569 athletes (719 women and 850 men) – specifically, 1162 swimmers (521 women, 641 men), 244 XC skiers (112 women, 132 men) and 163 biathletes (86 women, 77 men) – were included in the present study. Data were obtained from the databases of European Aquatics, the International Skiing Federation (FIS) and International Biathlon Union (IBU), with permission for data usage and publication of the scientific findings. If the data were not anonymized by the owner of the database, names were exchanged to unidentifiable codes before any further data processing and analysis. Formal written consent from the athletes was not required, as only publicly available data were used. The study protocol was approved by the institutional review board the Swiss Federal Institute of Sport Magglingen (Reg.-Nr. 222_03_2024) and is in accordance with the code of conduct of the World Medical Association for research studies involving human subjects (Declaration of Helsinki).

Athletes were divided into three performance groups: rank 1–8 (Top 8), rank 9–16 (Rank 9–16) and rank 17–30 (Rank 17–30), based on their best individual race result (across all disciplines excluding relay events) in one of the three analyzed WC. Subsequently, the youngest ages at which athletes reached various performance milestones at junior World championships (JWC) and adult WC – first appearance in the championships (debut; JWC-D and WC-D), first 17–30 rank (JWC-30 and WC-30), first 9–16 rank (JWC-16 and WC-16) and first top 8 rank (JWC-8 and WC-8) – were extracted from the same databases. Performance milestones were extracted from all individual events.

The three performance groups were clustered based on the top 8 swimmers competing in the finals, the best 16 swimmers qualifying for the semi-finals, and the best 30 XC skiers and biathletes qualifying for sprint races and mass start competitions, respectively. According to the regulations for junior competitions, ages at the performance milestones were determined by the age the athletes reached in the particular year of the competition. Biathlon JWC take place at the ages of 16–22 with an extra "Youth" category from 16 to 19 years of age. XC skiers compete in the JWC aged 16–20 and transition via the U23 WC to the adult WC. Swimmers compete in the JWC aged 14–18 before entering the adult WC. The official age categories of the international governing bodies were applied to contrast key structural elements of the respective talent development and competition systems. Although age categories at junior level differ between the sports, the JWC serve the same functional purpose and represent the final major international competition prior to the transition to the adult WC. Hence, the comparison of the various developmental pathways was used to offer insight into how different age policies affect progression and long-term athlete development.

All data are presented as means ± standard deviations. All analyses were performed separately for each sport and sex.[18] Data were normally distributed as shown by a diagonal straight line in the Q-Q plot and Gaussian distribution in the histogram. Linear mixed model analysis with fixed intercept and restricted maximum likelihood was used to compare *performance milestones* (JWC-D vs. JWC-30 vs. JWC-16 vs. JWC-8 vs. WC-D vs. WC-30 vs. WC-16 vs. WC-8) across the *performance groups* (Top 8 vs. Rank 9–16 vs. Rank 17–30). Ages at performance milestones were used as the dependent variable, while *performance milestones* and *performance groups* were used as fixed factors, and the *subject ID-code* as random factor. Bonferroni correction was applied to the *post-hoc* pairwise comparisons. The level of significance was set to $\alpha < 0.05$. All tests were performed using the Jamovi software package version 2.3.28.0 (Jamovi Project 2022, retrieved from https://www.jamovi.org).

3. Results

3.1. Performance milestones in swimming

Of the WC swimmers included in the present study, 41.6% (women 42.8%, men 40.6%) have had previously competed in JWC. Table 1

shows the average age when swimmers first reach the various performance milestones. Female and male swimmers showed the same overall development pattern across the various milestones, but the women were one year younger on average than men in both junior (16.1 ± 0.9 vs. 17.4 ± 0.8 years) and adult championship milestones (19.9 ± 3.3 vs. 21.2 ± 2.6 years), respectively. At junior level, there was no age difference ($p > 0.05$) between any of the performance milestones (JWC-D: 16.6 ± 1.1, JWC-30: 16.7 ± 1.1, JWC-16: 16.8 ± 1.0, JWC-8: 16.9 ± 1.0 years; average across women and men) or performance groups (Top 8: 16.7 ± 1.0, Rank 9–16: 16.7 ± 1.1, Rank 17–30: 16.8 ± 1.1 years; average across women and men). There was a significant age difference between the highest junior milestone (JWC-8: 16.9 ± 1.0) and adult competition debut (WC-D: 20.2 ± 2.9 years; $p < 0.001$; average across women and men). During the adult competitions, there was a significant difference ($p < 0.001$) between each performance milestones (WC-30: 20.5 ± 3.0 vs. WC-16: 21.1 ± 2.9 vs. WC-8: 21.4 ± 3.1 years; average across women and men), however, no age differences were found between the performance groups ($p > 0.05$).

3.2. Performance milestones in XC skiing and biathlon

A total of 87.7% (women 87.5%, men 87.9%) of XC skiers and 91.4% (women 88.4%, men 94.8%) of biathletes had competed in the JWC prior to the adult WC (Tables 2 and 3, respectively). The average age of XC skiers (18.9 ± 0.9 and 24.5 ± 3.1 years) and biathletes (18.8 ± 1.6 and 24.8 ± 2.9 years) was higher both at JWC and WC, respectively, compared to that of swimmers (16.8 ± 1.1 and 20.6 ± 3.0 years). In contrast to the sex differences evident in swimmers, there was no significant difference between average age milestones of female vs. male XC skiers (18.7 ± 1.0 vs. 19.1 ± 0.8 and 24.0 ± 3.4 vs. 25.0 ± 2.8 years) or biathletes (18.6 ± 1.8 vs. 19.0 ± 1.3 and 24.8 ± 3.2 vs. 24.9 ± 2.6 years) at junior and adult competitions, respectively. During junior competitions there was no significant age difference between the performance milestones and performance groups in either XC skiing or biathlon ($p > 0.05$). After that, there was a significant age difference in the transition from junior to adult competitions in both XC skiers (JWC-8: 19.2 ± 0.7 vs. WC-D: 23.5 ± 2.9 years; $p < 0.01$) and biathletes (JWC-8: 19.2 ± 1.7 vs. WC-D: 23.5 ± 2.5 years; $p < 0.001$). Top 8 XC skiers reached important adult milestones (WC-16) significantly earlier than lower ranked female (23.8 ± 3.4 vs. 26.4 ± 3.1 years, $p = 0.029$) and male skiers (25.0 ± 2.6 vs. 27.0 ± 3.3, $p = 0.013$). However, those lower performance groups' average age increased across the adult milestones ($p < 0.05$) for both female and male Rank 9–16 and Rank 17–30 XC skiers (WC-D: 23.5 ± 2.9, WC-30: 25.3 ± 2.8, WC-16: 26.3 ± 3.1 years; average across sex and performance groups). In biathlon, average age only increased significantly from WC-D to WC-30 in male Rank 9–16 and Rank 17–30 athletes ($p < 0.001$).

4. Discussion

When comparing age-related career trajectories across various technical whole-body endurance sports, swimming showed a lower number of adult WC participants who had previously competed in JWC (~40%) compared to XC skiing and biathlon (~90%). On average, swimmers were also 2 and 4 years younger at JWC and WC, respectively, than XC skiers and biathletes. In all three sports, there was a substantial 3–4 year age gap between the highest junior performance milestone and adult WC debut. Men and women showed the same overall development pattern, although female swimmers were, on average, one year younger when they reached the performance milestones. The swimmers' average age increased the more ambitious the performance milestones at WC. However, no age difference was found between the performance milestones at JWC level in any of the three sports. Swimmers showed no age differences between the performance groups, i.e. Top 8, Rank 9–16 and Rank 17–30 at neither JWC nor WC. However, the most successful XC skiers reached their adult performance milestones earlier (at a younger age) than their lower ranked peers.

Several factors may contribute to the considerably lower transition rate from JWC to adult WC in swimming (~40%) than in XC skiing and biathlon (~90%). As swimmers are on average younger at JWC level than XC skiers and biathletes, their final participation in JWC (typical about 18 years of age) coincides with the end of school attendance in most countries. Consequently, swimmers must bridge the critical 3–4 year gap between JWC and adult WC during this transitional life phase. Thus, the end of school attendance typically marks a critical decision point at which athletes must choose between

Table 1
Average age when reaching the various performance milestones at junior (JWC) and adult World championships (WC): championship debut (JWC-D, WC-D), first 17–30 ranking (JWC-30, WC-30), first 9–16 ranking (JWC-16, WC-16), first 1–8 ranking (JWC-8, WC-8) of *swimmers* across the various performance groups (Top 8 vs. Rank 9–16 vs. Rank 17–30).

Performance milestone	Performance groups			Linear mixed model analysis		
	Top 8	Rank 9–16	Rank 17–30			
Female swimmers						
WC-8	20.8 ± 3.4 (*n* = 177)*			$R^2_C = 0.81$	(a) $F_{[7 \mid 1795]} = 201$	$p < 0.001$
WC-16	19.9 ± 2.9 (*n* = 177)	21.1 ± 3.4 (*n* = 145)*		ICC = 0.76	(b) $F_{[2 \mid 620]} = 1$	$p = 0.312$
WC-30	19.4 ± 2.9 (*n* = 177)	20.2 ± 3.4 (*n* = 145)	19.8 ± 3.6 (*n* = 199)*		(c) $F_{[14 \mid 1788]} = 3$	$p < 0.001$
WC-D	19.3 ± 2.9 (*n* = 177)*	19.9 ± 3.3 (*n* = 145)*	19.2 ± 3.2 (*n* = 199)*			
JWC-8	16.1 ± 0.9 (*n* = 63)	16.3 ± 0.8 (*n* = 45)	16.6 ± 1.0 (*n* = 25)			
JWC-16	16.1 ± 0.9 (*n* = 73)	16.1 ± 0.9 (*n* = 56)	16.2 ± 1.1 (*n* = 44)			
JWC-30	16.1 ± 0.9 (*n* = 75)	16.0 ± 0.8 (*n* = 68)	16.0 ± 1.1 (*n* = 68)			
JWC-D	16.0 ± 0.9 (*n* = 76)	16.0 ± 0.8 (*n* = 68)	15.8 ± 1.1 (*n* = 79)			
Male swimmers						
WC-8	22.0 ± 2.8 (*n* = 197)*			$R^2_C = 0.83$	(a) $F_{[7 \mid 2157]} = 445$	$p < 0.001$
WC-16	21.3 ± 2.5 (*n* = 197)*	22.0 ± 2.4 (*n* = 154)*		ICC = 0.75	(b) $F_{[2 \mid 768]} = 1$	$p = 0.439$
WC-30	20.8 ± 2.3 (*n* = 197)	21.4 ± 2.4 (*n* = 154)	21.4 ± 2.7 (*n* = 290)*		(c) $F_{[14 \mid 2153]} = 3$	$p < 0.001$
WC-D	20.6 ± 2.3 (*n* = 197)*	21.1 ± 2.5 (*n* = 154)*	20.7 ± 2.7 (*n* = 290)*			
JWC-8	17.4 ± 0.7 (*n* = 71)	17.6 ± 0.6 (*n* = 47)	17.5 ± 0.6 (*n* = 41)			
JWC-16	17.3 ± 0.7 (*n* = 80)	17.5 ± 0.7 (*n* = 57)	17.5 ± 0.6 (*n* = 67)			
JWC-30	17.3 ± 0.7 (*n* = 87)	17.4 ± 0.8 (*n* = 63)	17.4 ± 0.8 (*n* = 93)			
JWC-D	17.3 ± 0.7 (*n* = 88)	17.3 ± 0.9 (*n* = 66)	17.1 ± 1.0 (*n* = 106)			

(a) Main effect: performance milestones (JWC-D vs. JWC-30 vs. JWC-16 vs. JWC-8 vs. WC-D vs. WC-30 vs. WC-16 vs. WC-8); (b) main effect: performance group (Top 8 vs. Rank 9–16 vs. Rank 17–30); (c) interaction effect: performance milestones × performance group. Post hoc comparison: * significant difference to the previous (i.e. lower) performance milestone, $p < 0.05$.

Table 2
Average age when reaching the various performance milestones at junior (JWC) and adult World championships (WC): championship debut (JWC-D, WC-D), first 17–30 ranking (JWC-30, WC-30), first 9–16 ranking (JWC-16, WC-16), first 1–8 ranking (JWC-8, WC-8) of *cross-country skiers* across the various performance groups (Top 8 vs. Rank 9–16 vs. Rank 17–30).

Performance milestone	Performance groups			Linear mixed model analysis		
	Top 8	Rank 9–16	Rank 17–30			
Female cross-country skiers						
WC-8	24.8 ± 3.7 ($n = 41$)			$R^2_C = 0.83$	(a) $F_{[7 \mid 536]} = 183$	$p < 0.001$
WC-16	23.8 ± 3.4 ($n = 41$)[16]	26.4 ± 3.1 ($n = 29$)*		ICC = 0.70	(b) $F_{[2 \mid 112]} = 1$	$p = 0.290$
WC-30	23.3 ± 3.5 ($n = 41$)	24.9 ± 3.1 ($n = 29$)	23.7 ± 2.7 ($n = 42$)*		(c) $F_{[14 \mid 535]} = 4$	$p < 0.001$
WC-D	22.9 ± 3.6 ($n = 41$)*	23.9 ± 2.8 ($n = 29$)*	22.5 ± 2.7 ($n = 42$)*			
JWC-8	18.8 ± 0.8 ($n = 27$)	19.3 ± 0.8 ($n = 12$)	19.5 ± 0.5 ($n = 15$)			
JWC-16	18.6 ± 1.0 ($n = 31$)	19.0 ± 0.8 ($n = 19$)	19.2 ± 1.0 ($n = 26$)			
JWC-30	18.4 ± 1.0 ($n = 34$)	18.8 ± 0.8 ($n = 24$)	18.9 ± 1.0 ($n = 36$)			
JWC-D	18.4 ± 1.0 ($n = 35$)	18.7 ± 0.9 ($n = 27$)	18.5 ± 1.1 ($n = 36$)			
Male cross-country skiers						
WC-8	26.0 ± 2.5 ($n = 41$)			$R^2_C = 0.83$	(a) $F_{[7 \mid 618]} = 312$	$p < 0.001$
WC-16	25.0 ± 2.6 ($n = 41$)[16]	27.0 ± 3.3 ($n = 36$)*		ICC = 0.51	(b) $F_{[2 \mid 140]} = 3$	$p = 0.061$
WC-30	24.1 ± 2.4 ($n = 41$)	25.3 ± 2.6 ($n = 36$)	25.2 ± 2.9 ($n = 55$)*		(c) $F_{[14 \mid 616]} = 2$	$p = 0.015$
WC-D	23.7 ± 2.6 ($n = 41$)*	24.8 ± 2.6 ($n = 36$)*	23.6 ± 2.5 ($n = 55$)*			
JWC-8	19.3 ± 0.7 ($n = 28$)	19.4 ± 0.7 ($n = 14$)	19.4 ± 0.7 ($n = 16$)			
JWC-16	19.2 ± 0.7 ($n = 38$)	19.3 ± 0.7 ($n = 24$)	19.3 ± 0.7 ($n = 27$)			
JWC-30	19.0 ± 0.7 ($n = 38$)	19.0 ± 0.8 ($n = 28$)	19.1 ± 0.8 ($n = 35$)			
JWC-D	18.7 ± 0.7 ($n = 38$)	19.0 ± 0.8 ($n = 29$)	19.0 ± 0.9 ($n = 49$)			

(a) Main effect: performance milestones (JWC-D vs. JWC-30 vs. JWC-16 vs. JWC-8 vs. WC-D vs. WC-30 vs. WC-16 vs. WC-8); (b) main effect: performance group (Top 8 vs. Rank 9–16 vs. Rank 17–30); (c) interaction effect: performance milestones × performance group. Post hoc comparisons: * significant difference to previous (i.e. lower) performance milestone;[16] different to Rank 9–16 performance group, $p < 0.05$.

pursuing a professional sporting career and entering another profession.[19] Due to the substantial training demands of elite swimming (up to 58 ± 10 km per week distributed across 9.9 ± 0.3 swimming and 3.6 ± 1.5 strength-training sessions totaling approximately 24 h per week including double-session days and early-morning session (e.g. 6 am))[20] combining high-level training with another profession or higher education becomes increasingly challenging. The missing financial perspective may further discourage young swimmers from choosing the professional sport career,[21] as even highly successful Olympic swimmers in most countries remain dependent on external financial resources, such as governmental grants or scholarships.[21] In contrast, biathletes and XC skiers compete in their junior categories for longer. The later transition to adult WC at the ages of 22 and 20 years, respectively, gives athletes more time to find dual-career pathways, gain financial stability and create a job perspective for after their sporting career,[22] hence contributes to the higher transition rate from JWC to adult WC.

Also, from a performance-perspective, bridging the 3-year age gap between highest junior milestone (top 8 at JWC) and adult WC debut presents a substantial obstacle. Successful junior swimmers must continue to progress in performance to reach a competitive level for adult competitions, yet without an intermediate competitive stepping stone between the JWC and WC. This transition may be even more challenging for female swimmers, who generally mature biologically earlier[23] and therefore tend to reach performance milestones approximately one year earlier than their male counterparts. The recently established U23 European championships intend to support the talent transfer from international junior to adult competitions. Nevertheless, based on the present findings and the beginning peak performance at the

Table 3
Average age when reaching the various performance milestones at junior (JWC) and adult World championships (WC): championship debut (JWC-D, WC-D), first 17–30 ranking (JWC-30, WC-30), first 9–16 ranking (JWC-16, WC-16), first 1–8 ranking (JWC-8, WC-8) of *biathletes* across the various performance groups (Top 8 vs. Rank 9–16 vs. Rank 17–30).

Performance milestone	Performance groups			Linear mixed model analysis		
	Top 8	Rank 9–16	Rank 17–30			
Female biathletes						
WC-8	26.3 ± 4.0 ($n = 39$)			$R^2_C = 0.86$	(a) $F_{[7 \mid 461]} = 234$	$p < 0.001$
WC-16	25.2 ± 3.4 ($n = 39$)	25.7 ± 3.1 ($n = 20$)		ICC = 0.66	(b) $F_{[2 \mid 85]} = 0$	$p = 0.898$
WC-30	24.6 ± 3.2 ($n = 39$)	25.2 ± 2.9 ($n = 20$)	24.9 ± 2.1 ($n = 27$)		(c) $F_{[14 \mid 460]} = 1$	$p = 0.550$
WC-D	23.5 ± 2.7 ($n = 39$)*	23.6 ± 3.0 ($n = 20$)*	23.4 ± 2.8 ($n = 27$)*			
JWC-8	19.1 ± 2.5 ($n = 30$)	19.1 ± 1.4 ($n = 15$)	18.8 ± 1.4 ($n = 15$)			
JWC-16	18.9 ± 2.0 ($n = 32$)	18.4 ± 1.2 ($n = 17$)	18.5 ± 1.2 ($n = 17$)			
JWC-30	18.9 ± 2.0 ($n = 35$)	18.2 ± 1.3 ($n = 18$)	18.4 ± 1.5 ($n = 20$)			
JWC-D	18.6 ± 2.1 ($n = 37$)	17.9 ± 1.3 ($n = 18$)	18.0 ± 1.5 ($n = 21$)			
Male biathletes						
WC-8	25.6 ± 3.2 ($n = 27$)			$R^2_C = 0.83$	(a) $F_{[7 \mid 420]} = 215$	$p < 0.001$
WC-16	25.1 ± 2.8 ($n = 27$)	26.9 ± 2.5 ($n = 23$)		ICC = 0.36	(b) $F_{[2 \mid 104]} = 2$	$p = 0.090$
WC-30	24.3 ± 1.7 ($n = 27$)	26.0 ± 2.4 ($n = 23$)*	25.4 ± 2.3 ($n = 27$)*		(c) $F_{[14 \mid 418]} = 2$	$p = 0.006$
WC-D	23.6 ± 1.9 ($n = 27$)*	23.6 ± 2.5 ($n = 23$)*	23.1 ± 2.0 ($n = 27$)*			
JWC-8	19.4 ± 1.1 ($n = 24$)	19.5 ± 1.3 ($n = 16$)	19.4 ± 1.4 ($n = 15$)			
JWC-16	19.1 ± 1.1 ($n = 27$)	19.2 ± 1.3 ($n = 17$)	19.1 ± 1.4 ($n = 23$)			
JWC-30	18.8 ± 1.1 ($n = 27$)	18.7 ± 1.1 ($n = 18$)	19.0 ± 1.4 ($n = 27$)			
JWC-D	18.7 ± 1.2 ($n = 27$)	18.5 ± 1.2 ($n = 19$)	18.6 ± 1.6 ($n = 27$)			

(a) Main effect: performance milestones (JWC-D vs. JWC-30 vs. JWC-16 vs. JWC-8 vs. WC-D vs. WC-30 vs. WC-16 vs. WC-8); (b) main effect: performance group (Top 8 vs. Rank 9–16 vs. Rank 17–30); (c) interaction effect: performance milestones × performance group. Post hoc comparison: * significant difference to previous (i.e. lower) performance milestone, $p < 0.05$.

age of 21 years,[1] the implementation of an U21 European championship may represent a more effective solution to bridge the gap between JWC and adult WC. All in all, increasing the transition rate from international junior to adult competitions enhances the likelihood of international medal success and improve the return of investment in resources devoted to the education and development of junior swimmers.[24]

The question is, why swimmers pursue such an early performance peak, which requires an early intensification of training and steep performance progression.[1–3] Particularly, the absence of impact forces and altered movement economy in the water[25] allow for an earlier increase in training volume, including two daily training sessions totaling 17.3 ± 5.3 h per week at an age of 15–17 years.[26,27] As a result, swimmers accumulate annual training volumes during adolescence that XC skiers and biathletes typically do not reach until adulthood.[20,26,28,29] XC skiers and biathletes follow a more gradual increase in training volume by approximately 55 h per year from 16 to 22 years of age.[28,29] This is necessary for the progressive development of exercise tolerance, particularly given that 36 ± 3% of the annual training volume is performed using non-specific exercise modes such as running.[30]

Adopting a less steep performance progression in swimming and allowing for a later performance peak may help bridge the 3 year gap between JWC and adult WC, thereby facilitating the transition of a greater number of talented athletes into adult competition, particularly those who develop more slowly but continuously toward adulthood.[31] Such an approach would especially benefit biologically late-maturing athletes and those born later in the selection year, who remain underrepresented in most talent development systems.[8,23] As several key performance determinants in swimming are strongly related to technical skill acquisition, swimmers specialize in a particular swimming stroke rather than race distance,[32–34] and may benefit targeted technical learning experiences at younger ages.[35] An emphasis on biomechanical and technical skill acquisition may also promote long-term performance improvements, as technical errors resulting from an excessive early focus on physiological capacity may persist and become difficult to correct in later stages of an athlete's career. Moreover, physical development can be effectively supported through targeted complementary training modalities like XC skiers and biathletes integrate multiple exercise modes, such as running, cycling, orienteering, and roller skiing, within their long-term training programs.[28–30]

In particular, land-based strength and conditioning represents an important complementary training modality for swimmers and has become increasingly relevant for preparing the explosive push-off required during starts and turns.[36] The recent inclusion of additional Olympic sprint events (50 m butterfly, backstroke, and breaststroke) provides further rationale for allocating time during the junior years to a comprehensive education in land-based resistance training exercise preparing for more advanced strength and conditioning routines involving heavy loads during adult age.[36] Although such an approach may slow performance progression during junior age, it is likely to establish a stronger foundation for performance during adult age and contribute to a more sustainable long-term development process.

A “lack of enjoyment” and “get bored” have been identified as major reasons why swimmers terminate their competitive careers.[5] The highly repetitive nature of swim training is characterized by covering the same pool lengths numerous times, which may exacerbate mental fatigue and reduce long-term motivation. Incorporating alternative exercise modes into swimming training could help disrupt monotonous routines, enhance enjoyment, and support psychological well-being. Given the lack of clear physiological explanations for swimmers' earlier career termination compared to other technical whole-body endurance sports, the strategic inclusion of varying training modalities may contribute to career longevity. Although this may attenuate performance progression during junior age, it may preserve motivation, facilitate a more gradual increase in training commitment, and ultimately shift the peak performance window toward the adult age, where performance outcomes are most consequential at international adult championships.

5. Conclusion

The present study revealed differences in age-related career trajectories across various technical whole-body endurance sports. Besides swimmers transitioning earlier from JWC to adult WC, they show a lower transition rate from JWC to adult WC compared to XC skiers and biathletes. Men and women in all three sports exhibit similar overall development patterns, although female swimmers reach performance milestones approximately one year earlier than males. Gradual performance progression and intermediate competitions alongside logistical, psychological and educational factors may help bridge the 3 year gap between junior and adult competitions and ultimately elongate peak performance window during adult age, where performance outcomes are most consequential at international adult championships.

Confirmation of ethical compliance

The study protocol was approved by the institutional review board of the Swiss Federal Institute of Sport Magglingen (Reg.-Nr. 222_03_2024) and is in accordance with the code of conduct of the World Medical Association for research studies involving human subjects (Declaration of Helsinki).

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Declaration of interest statement

The authors have no conflict of interest to report that may have affected data collection, analysis, or interpretation of the present study.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsams.2026.01.014.

Data availability

Raw data are publicly available on https://www.swimrankings.net/, https://api.fis-ski.com and https://www.biathlonresults.com/#/start.

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