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SYSTEMATIC REVIEW

Age of Peak Competitive Performance of Elite Athletes: A Systematic Review

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Abstract

Background Knowledge of the age at which elite athletes achieve peak performance could provide important information for long-term athlete development programmes, event selection and strategic decisions regarding resource allocation.

Objectives The objective of this study was to systematically review published estimates of age of peak performance of elite athletes in the twenty-first century.

Methods We searched SPORTDiscus, PubMed and Google Scholar for studies providing estimates of age of peak performance. Here we report estimates as means only for top (international senior) athletes. Estimates were assigned to three event-type categories on the basis of the predominant attributes required for success in the given event (explosive power/sprint, endurance, mixed/skill) and then plotted by event duration for analysis of trends.

Results For both sexes, linear trends reasonably approximated the relationships between event duration and estimates of age of peak performance for explosive power/sprint events and for endurance events. In explosive power/sprint events, estimates decreased with increasing event duration, ranging from ~27 years (athletics throws, ~1–5 s) to ~20 years (swimming, ~21–245 s). Conversely, estimates for endurance events increased with increasing event duration, ranging from ~20 years (swimming, ~2–15 min) to ~39 years (ultra-distance cycling, ~27–29 h). There was little difference in estimates of peak age for these event types between men and women. Estimations of the age of peak performance for athletes specialising in specific events and of event durations that may best suit talent identification of athletes can be obtained from the equations of the linear trends. There were insufficient data to investigate trends for mixed/skill events.

Conclusion Differences in the attributes required for success in different sporting events likely contribute to the wide range of peak-performance ages of elite athletes. Understanding the relationships between age of peak competitive performance and event duration should be useful for tracking athlete progression and talent identification.

Key Points

- Estimates of age of peak performance of elite athletes in the twenty-first century are collated in this review.
- The estimates decrease linearly with increasing event duration for explosive power/sprint events and increase linearly with increasing event duration for endurance events. The reversal occurs at ~21 years and events of ~4 min duration.
- The equations of these linear trends can be used to estimate the age of peak performance for athletes specialising in specific events, or to help guide event selection for talent identification and transfer athletes.

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1 Introduction

The aging process is a key driver of an athlete's physical and mental development, which in turn plays a critical role in determining their competitive performance [1]. Knowledge of age of peak performance in elite sport could provide coaches and scientists with valuable information to guide long-term training plans and to help gauge an athlete's progression towards their performance targets [2, 3]. Such information could also be beneficial for administrators making athlete-selection decisions for major competitions, and for national sporting organisations tasked with allocating funding and resources based on an athlete's chances of achieving future medal-winning success [4, 5].

Research into the age-related development of the human species indicates that various biological capacities typically reach their peak at different stages of an individual's life [6, 7]. For example, exercise physiology literature suggests that peak physiological function occurs just prior to age 30 years [8], whereas our ability to accumulate, integrate and apply cognitive skills has been shown to increase until at least age 60 years [9]. It therefore follows that the age of peak competitive performance is likely to vary between athletes from different sports and events, depending on the specific skills and attributes required for success in a particular event. Understanding the differences in the age–performance relationship between different event types could be useful for mature-age talent identification and transfer campaigns, similar to those recently undertaken by UK Sport and the Australian Institute of Sport [10]. These campaigns aim to systematically 'recycle' athletes with transferable talent characteristics developed from participating in popular sports with strong competitive fields, placing them into less popular sports with weaker fields in which athletic performance typically peaks at late enough ages to allow these athletes to develop the sport-specific skills required for Olympic medal-winning success.

Since the first comprehensive article of age of peak performance of top athletes was published in 1988 [1], this topic has become the focus of considerable research interest across a large number of sports. Researchers have employed typically one of three methods: identifying the age at which top athletes achieved their best performance; calculating the age of top-ranked athletes competing at pinnacle events such as the Olympics; or modelling the age of peak performance of top athletes using their age-related career performance data. One aim of such research has been to quantify the changes observed in age of peak performance of elite athletes over time. Studies of several different types of sports, including baseball [11], cycling [12], running [13], tennis [14] and triathlon [15], have consistently observed a marked increase in the age of peak performance of elite athletes between the end of the twentieth century and the beginning of the twenty-first century, presumably owing to factors such as recent advances in technology and greater opportunities for athletes to establish careers through their sporting success. Given this evidence, there is a clear need to investigate estimates of age of peak competitive performance in elite athletes of the twenty-first century, in order to establish findings relevant to the modern-day sporting environment.

The present article is the first systematic review on the topic of age of peak competitive performance of elite athletes. Here, we have documented the different methods used by researchers to quantify estimates of age of peak performance. We have also investigated differences in age of peak performance between different types of competitive events and we present estimates of age of peak performance relevant to modern-day athletes.

2 Methods

The methods used for this systematic review follow the structure outlined in the guidelines given by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement [16].

2.1 Data Search and Study Selection

At the start of October 2014 we undertook a web-based literature search for published estimates of the age of peak performance of elite athletes in different sports. Elite athletes were defined as those competing at the highest level of senior international competition possible in their respective sports. Unpublished articles were not included in the review owing to uncertainty in the robustness of their data and methods. We searched the SPORTDiscus and PubMed databases for the following terms: *(sport or athlete*) and performance and (age or longitudinal) and (peak or progress* or change* or effect)*. A search was also performed in Google Scholar for the key words *age peak performance sport*. This search produced an impractically large number of results (~280,000), with too many citations not relevant to this article. As such, additional studies were selected from Google Scholar using the option of searching related articles for relevant citations (this option was limited to 101 citations). One investigator (SVA) then screened all titles obtained through these searches and extracted only studies with appropriate abstracts for full review.

To be included in the literature review, the full-text article had to be written in English, contain a substantial proportion of data from after the year 1999, and report

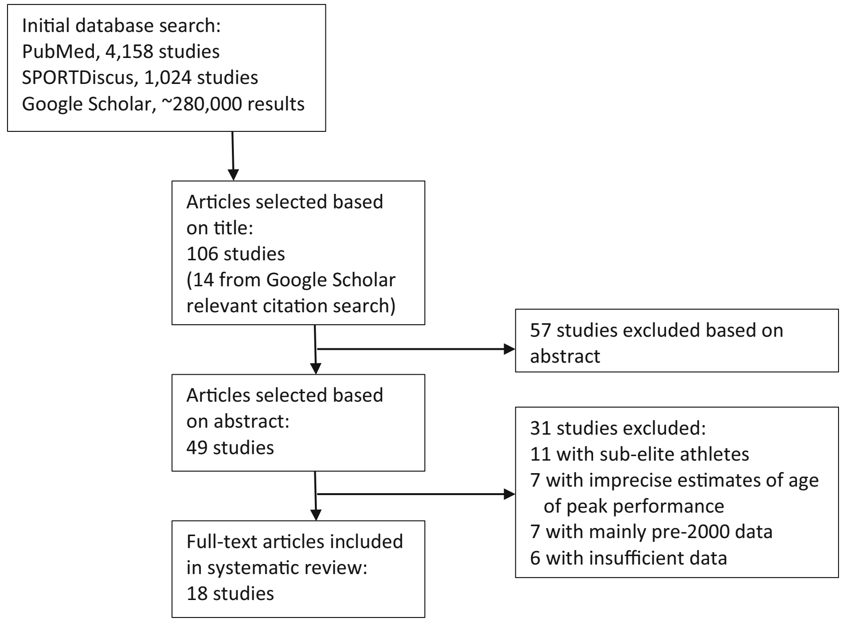

Fig. 1 Schematic representation of study search and selection process

either modelled estimates of the age of peak performance in a sport or data showing the age at which top athletes achieved their best performance in a sport. Studies reporting the age of top-ranked competitors in a sport or event were also included, provided they contained at least 3 years of data from ≥50 athletes competing at pinnacle events in the sport. We excluded 11 studies in which ages of peak performance were presented for sub-elite athletes (juniors, masters, national domestic or club-level athletes), seven studies that reported estimates of age of peak performance over a range of 5 or more years, seven studies with data predominantly from pre-2000 and six studies with insufficient data. No studies were excluded for reasons of poor quality. Figure 1 summarises our data search and study selection process.

2.2 Data Extraction and Analysis

Estimates of age of peak performance for top athletes of each sex in each sport and event are shown as means and standard deviations (SDs), with uncertainty expressed as 90 % confidence limits. For three studies in which categorical age and performance was investigated [17–19], estimates of the age range of peak performance are presented, but SDs and confidence limits were not available. Between-subject SDs are shown for studies in which individual age-related career performance trends were developed [4, 5, 17, 20] and for one study in which the age of best career performance of top athletes was calculated [3]. In studies where annual data on the age of top-ranked performers at pinnacle events over a number of years were presented [14, 15, 21–23], we chose to calculate means of annual age of peak performance from the year 2000 onwards, in order to generate estimates relevant to modern-day sport. To negate any confounding effects of secular trends, the presented SDs for these studies are the means of the between-subject SD for each year. Between-subject SDs could not be obtained for a number of studies in which fixed-effects models produced mean estimates of age of peak performance [17, 18, 24–26], but most authors provided standard errors for their models, which we used to compute confidence limits for these estimates. Attempts to contact authors of eight studies in which SDs and/or standard errors were not reported [14, 18, 21, 24–28] resulted in only one successful outcome [14].

To investigate differences in the age of peak performance between different kinds of events, estimates were split into three event-type categories on the basis of the predominant attributes required for success in the given event (explosive power/sprint, endurance and mixed/skill) and then plotted by event duration. For each event type with estimates across a sufficient range of event durations, we then added best-fit simple linear regression lines to create graphs that can be used for talent identification and event selection. By working through the data we found that the linear regression lines for both explosive power/sprint events and endurance events were a good fit for the estimates of peak age for middle-distance swimming (200–400 m events), presumably owing to the need for speed and endurance for successful performance in these events. We therefore chose to assign these estimates to both categories. Uncertainty in the accuracy of predictions made with these regression lines was expressed as standard errors of the estimate.

All 18 studies produced estimates of age of peak performance for male athletes, while corresponding estimates for their female counterparts were presented only by 13 of these studies. For studies where data were provided for both sexes, paired *t* tests were performed for each event type with a sufficient number of estimates (>5) using a published spreadsheet [29] to investigate the mean differences in age of peak performance between sexes. We used non-clinical magnitude-based inferences to assess these differences. With this approach, inferences about the true value of a difference were based on uncertainty in the magnitude of the difference: if the confidence limits overlapped values for a substantial increase and decrease, the difference was deemed unclear; otherwise, the difference was deemed clear and reported as the magnitude of the observed value [30]. Our smallest important difference was 0.64 year (0.2 of the combined between-subject SD for age of peak performance for all studies with available data, 3.2 years). Thresholds for moderate, large and very large differences were 1.9, 3.8 and 6.4 years, respectively (0.6, 1.2 and 2.0 of 3.2 years) [30]. Standard errors of the estimate for each of the regression lines were doubled for interpretation of their magnitude using this scale [31]. Uncertainty in mean differences was expressed as 90 % confidence limits and as likelihoods that the true value of the effect represents a substantial difference between sexes [32].

3 Results

The retrieved estimates of the age of peak performance of top athletes of each sex in each sport and event are summarised in Table 1 and plotted for analysis of trends in Fig. 2. In Fig. 2, mean estimates of the age of peak performance for each of the three event types are shown by event duration. For both sexes, clear and opposite trends were evident for explosive/sprint events and for endurance events. In explosive/sprint events, estimates showed a similar decrease with increasing event duration for males and females, ranging from a peak age of ~27 years for throwing events in athletics (~1–5 s) to ~20 years for swimming events (~21–245 s). In endurance events, estimates of peak age increased markedly with increasing event duration in both sexes, ranging from ~20 years for swimming events (~2–15 min) to ~39 years for ultra-distance cycling (~27–29 h). Patterns for mixed-skill events could not be discerned, owing to the smaller number of estimates retrieved for this event type.

Equations for the best-fit linear regression lines and corresponding standard errors of the estimate for each sex and event-type combination are also shown in Fig. 2. The magnitude of these standard errors was large for female endurance events, and moderate for all other sex and event-type combinations. By using simple algebra, we were able to solve the simultaneous equations for explosive/sprint and endurance events for each sex to reveal the points of intersection of the regression lines: event durations of ~4 min (279 s for males, 241 s for females).

For studies where estimates of age of peak performance were presented for both sexes, male explosive/sprint athletes displayed a higher peak-performance age than their female counterparts by a borderline trivial–small mean amount of 0.6 years (90 % confidence limits ±0.7 years, possibly substantial). In endurance events, the mean difference in age of peak performance between males and females was trivial in magnitude but unclear (0.1 ± 1.0 years).

4 Discussion

In this systematic review we have reported estimates of age of peak performance of elite athletes for different sports and events from 18 studies. By plotting mean estimates by event duration, we have shown that clear and opposite linear trends reasonably approximate the relationships between event duration and age of peak performance for explosive power/sprint events and for endurance events. The equations of these linear trends have provided a tool that can be used either to help assess the future prospects of an athlete specialising in a particular event based on their predicted age of peak performance, or to help direct event selection for mature-age talent identification and transfer athletes. Given that the points of intersection of these linear trends occurred at event durations of approximately 4 min for both sexes, athletes typically competing in events shorter than this duration should use the explosive/sprint equations to estimate their age of peak performance, whereas the endurance equations are more appropriate for those specialising in longer events.

Our findings that age of peak performance tended to decrease with increasing event duration for events in which performance is determined mainly by explosive power output and sprint ability may reflect the differing contributions of skill and technique to performance in these events. Throwing events in athletics (~1–5 s) involve coordination of a sequence of complex motor patterns within a rapidly executed single effort in order to efficiently transfer explosive power to the thrown implement [33], which inevitably requires many years of training and experience to master [5]. In athletics track sprint events (~10–55 s), gross motor patterns are repeated over a number of stride cycles, so performance in these events is likely more dependent on expression of raw power than on acquisition and application of skill [5]. Although technique is also a critical determinant of performance in sprint and middle-distance swimming (~21–245 s) [34, 35], the

Table 1 Estimates of age of peak performance of elite athletes separately by event, event type, sport and sex. Information regarding event duration, method of estimation of peak age, and subjects and data included in the analysis are also shown

Event type, sport and study	Event	Event duration[a]	Method	Subjects and data	Men[b]		Women[b]	
					Age of peak	90 % CL	Age of peak	90 % CL
Explosive/sprint								
Athletics								
Berthelot et al. [25]	Sprints[c]	10–50 s	Mean exponential growth and decay curve	Best annual career performances of world-ranked top 10 (1980–2009)	25.8	?	25.7	?
Hollings et al. [5]	Sprints, hurdles[d]	10–55 s	Individual quadratic curves via mixed modelling	All competition performances of world-ranked top 12 (field) or top 16 (track) (2000–2009)	25.2 ± 2.3	0.3	25.7 ± 2.4	0.3
	Jumps[e]	5 s			25.8 ± 2.1	0.3	25.6 ± 2.7	0.4
	Throws[f]	1–5 s			28.0 ± 2.5	0.4	26.7 ± 3.3	0.6
Tilinger et al. [26]	Sprints[g]	10–20 s	Mean quadratic curve via regression	16 world-prominent sprinters	24.5	?	–	–
	Jumps[h]	5 s		55 world-prominent jumpers	24	?	–	–
	Throws[i]	1 s		31 world-prominent throwers	26.5	?	–	–
Swimming								
Allen et al. [4]	50–100 m all Olympic events	21–65 s	Individual quadratic curves via mixed modelling	Best annual career performances of Olympic top 16 (2008, 2012)	25.0 ± 1.9	0.3	23.3 ± 2.8	0.6
Berthelot et al. [25]	50–100 m free	21–54 s	Mean exponential growth and decay curve	Best annual career performances of world-ranked top 10 (1980–2009)	22.4	?	22.8	?
Sokolovas [3]	50–100 m all Olympic events	21–65 s	Age at best career performance	Top 10 best swimmers in history	23.1 ± 2.6	0.6	21.3 ± 4.1	1
Wolfrum et al. [19]	50–100 m breast	27–65 s	Age group of top-ranked performers at pinnacle events	Top 8 World Championships finishers between 2003 and 2011	26–27		22–23	
	50–100 m free	21–54 s			28–29		24–27	
Endurance								
Athletics								
Hollings et al. [5]	Middle-distance[j]	0.03–0.5 h	Individual quadratic curves via mixed modelling	All competition performances of world-ranked top 12 (2000–2009)	24.9 ± 2.4	0.3	26.7 ± 3.0	0.5
Berthelot et al. [25]	Middle-distance[k]	0.03–0.5 h	Mean exponential growth and decay curve	Best annual career performances of world-ranked top 10 (1980–2009)	25	?	25.3	?
Berthelot et al. [25]	Marathon	2.1–2.3 h	Mean exponential growth and decay curve	Best annual career performances of world-ranked top 10 (1980–2009)	31 .6	?	27.1	?
Hunter et al. [22]		2.1–2.3 h	Age of top-ranked performers at pinnacle events	Top 5 World Marathon Majors finishers (2000–2009)	28.8 ± 3.7	0.4	29.8 ± 3.8	0.4
Cejka et al. [21]	100 km ultra-marathon	6.5–7.5 h	Age of top-ranked performers at pinnacle events	Annual top 10 fastest athletes from all top races (1960–2012)	34.5 ± ?	0.2	34.9 ± ?	0.2
Rüst et al. [23]	100 mile ultra-marathon	12–14 h	Age of top-ranked performers at pinnacle events	Top 10 finishers from all top races (2000–2011)	37.3 ± 6.3	0.3	38.6 ± 5.6	0.2

Table 1 continued

Event type, sport and study	Event	Event duration[a]	Method	Subjects and data	Men[b]		Women[b]	
					Age of peak	90 % CL	Age of peak	90 % CL
Cycling								
Anderson [24]	Cyclo-cross	1 h	Mean quadratic curve estimated from race rankings	103 cyclo-cross riders across 8 World Cup races (2012–2013)	30.2	?	–	–
Shoak et al. [12]	Ultra-distance	27–29 h	Age of top-ranked performers at pinnacle events	Furnace Creek 508 and Swiss Cycling Marathon winners (2000–2011)	38	1.8	39	2.5
Swimming								
Allen et al. [4]	200–1500 m all Olympic events	0.03–0.25 h	Individual quadratic curves via mixed modelling	Best annual career performances of Olympic top 16 (2008, 2012)	23.6 ± 1.9	0.3	22.1 ± 2.0	0.3
Berthelot et al. [25]	200–1500 m free	0.03–0.25 h	Mean exponential growth and decay curve	Best annual career performances of world-ranked top 10 (1980–2009)	20.4	?	20	?
Sokolovas [3]	200–1500 m all Olympic events	0.03–0.25 h	Age at best career performance	Top 10 best swimmers in history	21.7 ± 2.5	0.5	19.8 ± 3.1	0.6
Wolfrum et al. [19]	200 m breast	0.04 h	Age-group of top-ranked performers at pinnacle events	Top 8 World Championships finishers between 2003 and 2011	20–21		22–23	?
	200 m free	0.03 h			22–23		22–23	?
Triathlon								
Malcata et al. [20]	Olympic-distance	1.8–2.1 h	Individual quadratic curves via mixed modelling	All competition performances of top 30 triathletes (2000–2012)	27.6 ± 2.1	0.6	27.1 ± 3.6	1.1
Rüst et al. [15]	Ironman	8–9 h	Age of top-ranked performers at pinnacle events	Top 10 at World Championships every year (2000–2012)	32 ± 3	0.4	34 ± 4	0.5
Mixed								
Ice hockey								
Brander et al. [17]		1 h	Age group of top-ranked performers	Scoring index for top 10 NHL forwards (1997–2012)	27–29		–	–
			Age group (1-year categories) with best mean performance	Scoring index for all NHL forwards (1997–2012)	28		–	–
			Mean cubic curve via regression		27.6	0.4	–	–
			Individual quadratic curves		27.7 ± 3.3	0.2	–	–
			Age group of top-ranked performers	Plus-minus index for top 10 NHL defencemen (1997–2012)	23–33		–	–
			Age group (1-year categories) with best mean performance	Plus-minus index for all NHL defencemen (1997–2012)	27		–	–
			Mean quadratic curve via regression		27.8	3	–	–
			Individual quadratic curves		28.2 ± 3.9	0.4	–	–

Table 1 continued

Event type, sport and study	Event	Event duration[a]	Method	Subjects and data	Men[b]		Women[b]	
					Age of peak	90 % CL	Age of peak	90 % CL
Tennis								
Guillaume et al. [27]		2–3.5 h	Individual exponential growth and decay curves	Top 10 world-ranked players (1985–2009)	23.3 ± ?	?	21.5 ± ?	?
Kovalchik [14]			Age of top-ranked performers	Top 30 world-ranked players (2000–2012)	25.8 ± 3.1	1	–	–
Skill								
Golf								
Fried and Tauer [18]		5 h	Rolling mean (1-year categories)	Earnings index of PGA tour golfers (2004–2006)	36	?	–	–
			Mean quadratic curve via regression		35	?	–	–
Tiruneh [28]		5 h	Age of top-ranked performers at pinnacle events	PGA tour winners (2003–2007), LPGA tour winners (2002–2006)	35.1 ± 6.2	0.7	29.9 ± ?	?

breast Breaststroke, *CL* confidence limits, *free* freestyle, *LPGA* Ladies Professional Golf Association, *NHL* National Hockey League, *PGA* Professional Golf Association, *SD* standard deviation

[a] Approximate range of event durations are shown for top performers in each event

[b] Data are mean ± SD, apart from for methods estimating an age group (range) of peak mean performance. Between-subject SDs are shown for methods with individual age-performance trends and for methods investigating age at best performance. For methods investigating age of top-ranked performers at pinnacle events over a number of years, a mean of the between-subject SD for each year is presented. SDs are missing where between-subject SDs could not be obtained owing to the nature of the method utilised. The ? symbol denotes that information required to calculate between-subject SDs or 90 % CLs was not provided. The – symbol denotes that estimates were not generated for women

[c] 100 and 400 m runs

[d] 100, 200 and 400 m runs; 100 m (women), 110 m (men) and 400 m hurdles

[e] High jump, long jump, pole vault, triple jump

[f] Discus throw, hammer throw, javelin throw, shot put

[g] 100 and 200 m runs

[h] Long jump, pole vault

[i] Discus, shot put

[j] 800, 1500 and 3000 m steeple, 5000 and 10,000 m runs

[k] 800, 1500, 5000 m (men) and 10,000 m runs

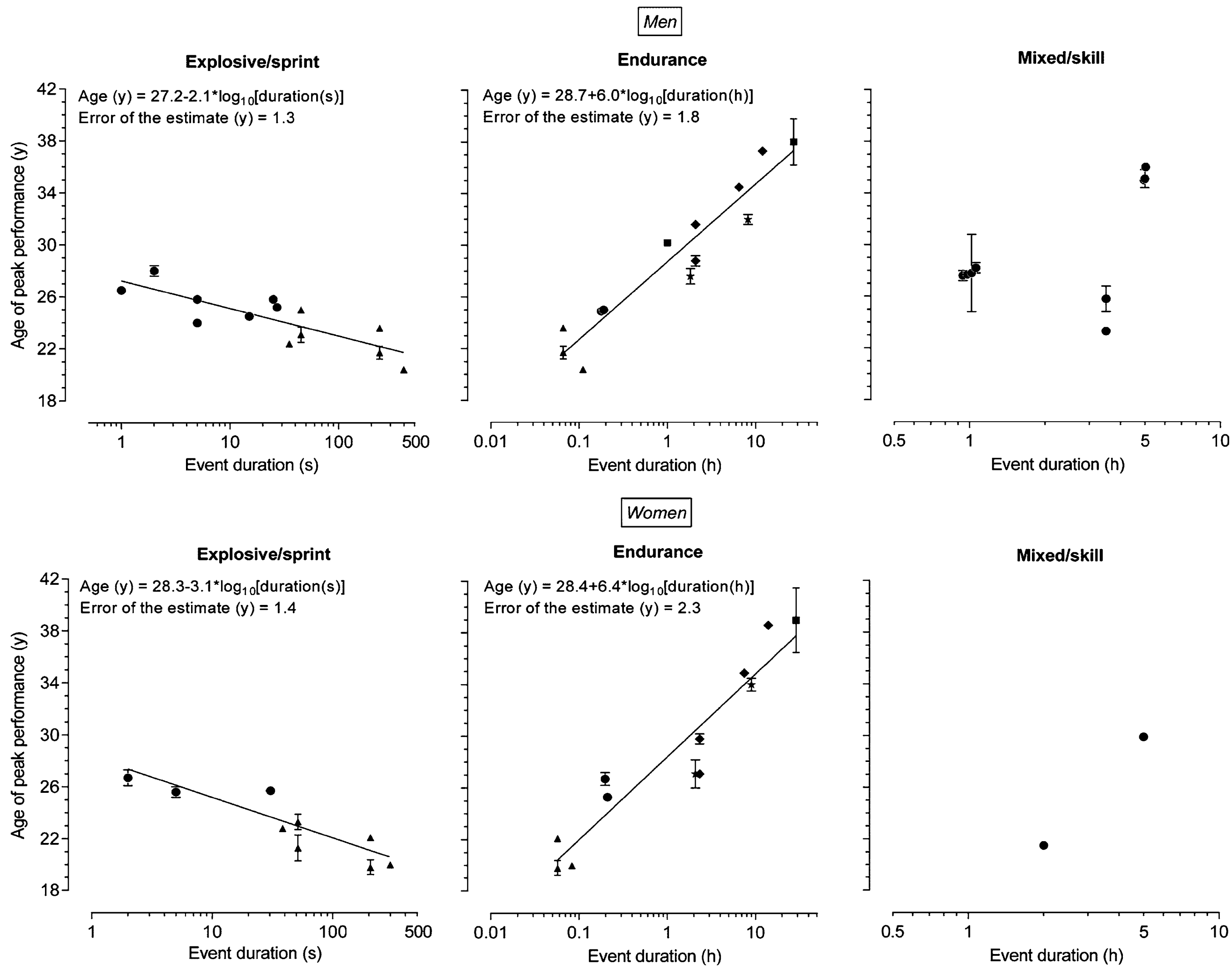

Fig. 2 Age of peak competitive sporting performance (mean ± 90 % confidence limits) of elite male and female athletes, shown by event duration (*logarithmic scale*). Where a grouped estimate is presented for multiple events of different durations, the duration shown is a mean for those events. Data are presented separately for three different event types: explosive/sprint events, endurance events, and mixed/skill events. For explosive/sprint events and endurance events, the following symbols represent estimates for different sports: *square* cycling, *diamond* running, *triangle* swimming, *circle* track-and-field athletics, *star* triathlon

younger age of peak performance observed for athletes in these events may relate to differences in the typical age of specialisation in a certain sport between swimmers and athletes from most other sports. For example, among the Olympians of 2004, the mean age of specialisation reported by swimmers was 8 years, compared with 14 years for athletics competitors [10]. While the kinesthetic learning and reinforcement needed to develop and maintain the efficient aquatic motion necessary for successful swim performance is thought to require greater time investment than that for successful performance in most land-based sports [36], it is likely that early specialisation at least partially contributes to the early peaking phenomenon observed in swimmers.

The trend of increasing age of peak performance with increasing event duration for events in which performance is primarily contingent upon endurance has been documented previously within studies of age of peak performance across multiple events [1, 37]. One explanation for this trend may be that physical attributes important for success in ultra-endurance events, such as aerobic capacity and movement economy, generally increase progressively with increasing training histories and thus age [38]. However, research into the age-related development of the human species shows that most physical capacities tend to peak around the age of 30 years [8], implying that factors other than physiology must contribute to the older estimates observed for events such as marathon running, Ironman triathlon, ultra-endurance cycling and cyclo-cross (e.g. pacing and nutritional strategies, anticipating and dealing with environmental conditions, and mental resilience). In some events it may therefore be possible for older athletes to continue progressing by accumulating improvements in cognitive and/or experiential capacities that offset the inevitable plateau in physical ability. This explanation aligns well with evidence that increased age is often associated with improved job performance. Despite well-established declines in indicators of fluid intelligence (e.g. problem solving, speed of information processing) from age ~27 years onwards, corresponding impairments in job performance beyond this age are rarely observed, owing to the human capacity to continue accumulating crystallised intelligence (e.g. knowledge, experience) until the age of at least 60 years [9].

Overall, it seems possible to reach peak performance at much older ages in endurance events than in explosive/sprint events. This difference may be explained by the fact that the shorter duration and higher absolute intensity of explosive/sprint events mean it is much harder for athletes in these events to offset declines in their physical ability with any gains in knowledge, experience, skill and/or cognitive ability. Indeed, one proposed explanation for the lack of observable declines in job performance of older adults is that human physical and cognitive capacities are often assessed at their maximal level of functioning, but are very seldom used at that level [9].

Interestingly, the points of intersection of the linear trend lines for explosive/sprint and endurance events occurred at event durations of ~4 min for both sexes. This value is somewhat greater than the 1–2 min duration of maximal exercise at which physiology research shows that equal contributions of energy are typically derived from the anaerobic and aerobic energy systems [39]. This discrepancy appears to be explained by our inclusion of middle-distance swimming (200–400 m events) within both explosive/sprint and endurance event types. However, more research from different sports is needed to further understand the age of peak performance in events with durations around this physiological crossover point (e.g. 500 m flatwater kayaking, 1500 m short-track speed skating).

While our literature search did not yield a sufficient number of estimates for trends to be quantitatively investigated for sports in the mixed/skill category (ice hockey, tennis, golf), observation of the available estimates reveals that peak performance in these events can be achieved at a wide range of ages, presumably depending on the contribution of physical, technical and tactical capacities to performance in each event. For example, the low physical demands of golf combined with the high importance of skill and mental fortitude for performance would seem to fit with the relatively high age of peak performance (~35 years). Perhaps surprisingly, given the apparent importance of accumulating physical fitness, skill and tactical knowledge for success in racquet sports, ages of peak performance for tennis players were reasonably young (~24 years). However, data from one study did show a progressive yearly increase in the annual average age of top-30 ranked tennis players, with estimates of peak age rising from ~25 years in 2006 to ~27 years in 2012 [14]. While these data led the author to speculate that this shift in the age of the world's top tennis players was reflective of evolution in the factors critical for performance success in the sport (e.g. greater endurance), these factors may have always been critical for successful tennis performance, but with recent advances in science, technology and funding/resource provision for athlete development, more players have begun to develop them. Similar to that in swimmers, early specialisation has typically been common in tennis players [36], potentially leading to artificially early ages of peak performance. With the improved long-term athlete development plans of modern-day national sporting organisations, the observed ages of peak performance of athletes in these sports may start to more closely reflect the ages at which the physical, mental, technical and strategic capacities required for successful performance typically peak within humans. If so, we would also expect to observe corresponding improvements in the standard of performance of these sports in the coming years as the capacity of their top athletes evolves.

Of the studies that investigated changes in age of peak performance of top athletes over a number of years, five contained evidence of trends showing annual increases in age of peak performance since the year 2000 [12, 14, 15, 21, 27]. Five studies also included a substantial proportion of data from athletes prior to the year 2000 [3, 21, 25–27], which we were unable to exclude from our results owing to either the analysis method of the study or the manner in which authors presented their estimates. Given this evidence, it is likely that differences in datasets were at least partly responsible for the between-study differences in estimates of peak age for similar events.

Another factor that probably contributed to the variation observed between peak age estimates for similar events was differences in the methods used to quantify age of peak performance. Indeed, one study quantified age of peak performance of ice hockey players using four different methods, producing estimates that varied by ~1–2 years [17]. For studies in which the age of top-ranked performers in an event was investigated, peak age estimates may be slightly elevated, owing to the fact that older athletes are likely to be higher ranked than their younger counterparts. Additionally, studies that employed either this method or the method of identifying the age at which top athletes achieved their best performance may have mis-estimated the timing of an athlete's true performance peak if it happened not to coincide with a major competition. While studies that used statistical modelling to quantify age of peak performance were not subject to these limitations, estimates produced by fixed-effects modelling of mean age–performance relationships do not appropriately account for the individual differences in these relationships that inevitably exist. Studies that modelled unique age and performance trends for each individual athlete may therefore have produced the most robust age of peak performance estimates; however, these estimates may also have been affected by differences in the availability of each athlete's career performance data, given that a minimum number of observations (typically three to five) are required to produce a peak age estimate for an individual.

On the whole, between-study differences (standard errors of the estimate) in estimates of peak age for similar events were moderate to large but our regression equations for each sex and event-type combination should still be useful to help predict the age of peak performance in a given event. If more authors had provided SDs and standard errors or confidence limits for their peak-age estimates, it would have been possible to weight and meta-analyse the study estimates, which would probably have improved the precision of our prediction equations. Given these limitations, readers should be mindful to consider the typical differences (SDs) between athletes of each sex and event type (Table 1) when using our equations to predict the age of peak performance in a given event.

With a greater number of peak-age estimates for female athletes, we would also have been able to meta-analyse the differences between sexes. As it was, males were possibly older at their peak performance than females in explosive/sprint events, which can presumably be explained by the earlier onset of puberty in females [40]. A similar pattern may also exist for endurance events, but more studies are required.

Given the ongoing evolution of age of peak performance in many sports, as noted above, future research should continue to track these trends in order to provide peak age estimates valid for current athletes. There is also a need for further research into the age of peak performance in more mixed/skill-based sports, as the majority of published articles were for sports with a predominant explosive power/sprint or endurance component. This imbalance likely reflects the difficulty of operationalising performance in sports without objective measurement of an individual's performance (time, distance or score), such as most team sports and judgement-based sports, including combat sports, diving and gymnastics. Further research into explosive power/sprint and endurance events from a wider range of sports (e.g. kayaking, rowing, speed skating, skiing) is also warranted in order to investigate the validity of using linear trends to describe the relationships between event duration and age of peak performance.

5 Conclusion

The age of peak competitive performance of elite athletes ranges widely between different events, likely owing to differences in the attributes required for success between events and differences in the points at which these attributes typically reach their peak capacity within an athlete's career. In explosive power/sprint events and endurance events, linear trends seemed to reasonably describe the relationships between age of peak performance and event duration. By estimating the equations of these trends, we have created a tool that may be useful for predicting the age of peak performance of athletes specialising in specific events, and for helping identify events that may best suit mature-age talent identification and transfer athletes.

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