encyclopedia

MDPI

Review

From Progression to Regression: How Running Performance Changes for Males and Females Across the Lifespan

Christopher R. Harnish [1,*] and Thomas C. Swensen [2]

[1] Department of Pediatrics, School of Medicine, Virginia Commonwealth University, Richmond, VA 23219, USA
[2] Department of Exercise and Sports Sciences, Ithaca College, Ithaca, NY 14850, USA; tswensen@ithaca.edu
* Correspondence: christopher.harnish@vcuhealth.org

Abstract

Running enjoys worldwide popularity across age groups and sexes. Because of this, it serves as an excellent benchmark to compare male and female performance across the lifespan with respect to developmental progression, peak athletic performance, and age-related regression. The purpose of this review is to examine and discuss how sex and aging affect running performance in sprints, middle-distance running, and long-distance running. Based on the scientific literature and running world records from age 5–99, male running performance exceeds that of females across the lifespan, with the greatest divide beginning at puberty, which remains through old age. However, there appear to be few differences in the rate of progression in youth and the age of peak performance, but it is unclear whether the rate of decline, beginning in middle age, differs by sex and sport for record performances. Future analyses should examine changes in all running performances across the lifespan.

Keywords: sex difference; pediatric exercise; human performance; aging; marathon; fundamental movement skills; adolescence; puberty; track and field

check for updates

Academic Editors: Antonio Cicchella and Raffaele Barretta

Received: 26 March 2025
Revised: 19 May 2025
Accepted: 23 June 2025
Published: 27 June 2025

Citation: Harnish, C.R.; Swensen, T.C. From Progression to Regression: How Running Performance Changes for Males and Females Across the Lifespan. *Encyclopedia* **2025**, *5*, 88. https://doi.org/10.3390/encyclopedia5030088

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Evolutionarily speaking, humans are seemingly born to run, with anatomical, physiological, and cognitive adaptations that favor endurance exercise [1]. Those latter adaptations predominantly benefit performance in distance running events (5 km or longer) but also influence performance in shorter running and even sprint events. While humans are regarded as comparatively slow compared to most other species [2], the pursuit of sporting excellence still drives the desire to achieve excellence in all sports. Therefore, it is no surprise that world records are tracked in nearly every possible endeavor in both men and women across the lifespan. Modern society has allowed amateur athletes as young as 5 years old (yo) and older than 100 yo to compete and achieve records in numerous sports.

As suggested, few sports are as fundamental to humans as running, and, as such, records are maintained for events ranging from 50 m to longer than 100 miles, with continuous improvements since the 1970s [3,4]. With these improvements, world records have proliferated in all events for both males and females as young as 5–6 yo. While progression in elite record performances has slowed in many running events, Masters (age 35 years and older) world records continue to improve more steeply, indicating that age-related declines in physical performance are perhaps less significant than believed [5]. Meanwhile, the emergence and rate of progression for junior athletes (13–18 yo) seem to be accelerating, though success at the senior elite level remains elusive for many athletes [6–11].

The proliferation of advanced training methods [12] and their application, as well as new technology [13], appears, in part, to be driving performance progression across age groups. Nonetheless, the gap between adult men and women has stayed relatively stable. Regardless of the underlying reasons for improved running performances, running records provide a rawer representation of human performance than records in other sports, like cycling, which is more influenced by external technological factors. As such, running records are truer to the evolved purpose of the body.

Many studies have examined various aspects of running performance across distances between elite men and women [14–19] and across ages for boys and girls [20–23] and men and women [5,23–29]. Numerous studies have modeled various aspects of the running distance spectrum [16,17,22,23,25–28,30]. However, we know of no review that has attempted to assimilate and summarize the major studies for review and discussion of our current understanding of the influence of sex and aging on running across the lifespan. Therefore, the purposes of this review are to

- Review the determinants of running events for sprints, middle-distance running, and long-distance running;
- Summarize the major developmental changes that occur in youth to adulthood and then senescence;
- Note the known sex differences in running performance across developmental stages;
- Discuss the progression and eventual regression of running performance across the lifespan;
- Propose future research questions to advance our understanding of these topics.

2. Defining Terminology, Development, and Performance

The breadth and complexity of this topic require defining the terminology, developmental stages, and performance aspects of the sport of running. For the purposes of this paper, we use the National Institutes of Health's definition of biological sex as a multidimensional biological construct based on anatomy, physiology, genetics, and hormones. Simple age demarcations between developmental stages, however, are more challenging. Definitions and distinctions within the literature vary in nomenclature, milestones, and developmental changes such as the onset of puberty, age of peak performance, and sports age groups [14–18]. Therefore, we have assimilated several sources and integrated these with the accepted age groupings in running, as reflected in world record running performances. The developmental stages used throughout the paper are as follows:

- Childhood (Ch)—from age 5 to 10 yo—which typically refers to the years preceding puberty.
- Adolescence (AD)—from age 11 to 18 yo—which typically marks the beginning of puberty to early adulthood. Where appropriate, we delineate early AD (EAD) as 11–14 yo and late (LAD) as 15–18 yo to better capture pubertal changes.
- Early Adulthood (EA)—from age 19 to 35 years. This is the period where running performance peaks and is generally maintained for both elite and age-group athletes.
- Middle Adulthood (MA)—from age 36 to 55 years. During this period, most athletes can maintain a very high level of performance with minimal performance loss.
- Late Adulthood (LA)—from age 56 years and beyond; this is the period where performance declines become more noticeable, with significant and accelerated declines after age 70.

Running performance is typically measured solely by time; thus, world records are reported as the lowest time over a given distance on a certified course. Prior to the age of 21, records and competitive events are often separated in 2-year increments, so ages 5–6, 7–8, 9–10, etc., compete together. After age 20, many sports, including running and triathlon, delineate ages in 5-year blocks, especially for Masters runners of 35 years and older; these

would be 35+, 40+, 45+, etc. However, to streamline data presentation for running record data, we present age groups in 10-year ranges after age 30 with developmental ranges highlighted and limit our running analysis to age 99 due to the limited number of records for 100 and older.

Finally, this paper will discuss what is known regarding the determinants or advantages influencing performance across different events. In some cases, we will refer to specific physiological or anatomical measurements, but for childhood, we will also refer to fundamental movement skills (FMS). These are basic components that make up the complex sports skills needed for daily activities, as well as success in running. These include, but are not limited to, the following: jumping, skipping, galloping (locomotor), static and dynamic balance (postural), and throwing, catching, and kicking (object control) [19]. As discussed later, even small differences in FMSs can confer significant sporting advantages as well as encourage continued participation in exercise and sports.

3. Competitive Running Distances and Determinants

Prior to any discussion of the determinants of running performance, we need to clearly define the distance demarcations in running. Regardless of whether events take place on a measured track or open road, competition distance typically consists of sprints, middle-distance events, and long-distance events. While there is justification for consistency in terminology in sports and research [20], for simplicity's sake, we will rely on the World Athletics-defined distance categories for *sprints*—100 m, 200 m, 400 m; *middle-distance running*—800 m, 1500 m (or mile), and 3000 m; and *long-distance running*—5000 m, 10,000 m, half-marathon, and marathon [21]. However, to distinguish between long-distance track-specific and road events, we define *middle–long-distance running* as 5000–10,000 m and *long-distance running* as half-marathons (13.1 km) and marathons (26.2 km). Aside from distance delineations for the various events, physiologists also classify them based on the energy or ATP demands and how they are met. It must be noted that energy contributions for many events are at best approximations based on a range of sources and likely underestimate the true "anaerobic" systems in many athletes [22].

3.1. Physiological Determinants of Sprint and Middle-Distance Running

Sports performance is dictated by numerous factors, including skill and coordination, neuromuscular and bioenergetic systems, vascular and cardiorespiratory function, and psychological factors. This section briefly reviews the most salient factors influencing sprint and middle-distance events, where competitors often overlap and where "anaerobic energy systems" either play a dominant or significant role, and neuromuscular and/or biomechanical factors are essential for achieving optimal performance [20].

3.1.1. Sprint Events (100–400 m)

The determinants for 100–200 m sprint distances are simple, relying on high muscular force applied at the start, rapid acceleration to the maximum speed, and eventual deceleration. For example, world-class 100 m sprinters typically accelerate for ~60 m before slowing in the final 40 m. The high forces needed to accelerate explosively require elite performers to possess a high percentage of Type II muscle fibers. One-hundred-meter sprints are powered primarily by the ATP-PCr and glycolytic energy systems [23] but also include a significant aerobic energy contribution [24], which increases with sprint distance [25]. Biomechanical and neuromuscular factors are critical to success and intimately tied to technique [26]. High-performance sprinters also possess a greater stride length (SL), particularly within the first 20 m, and exhibit greater ground reaction forces (GRFs) with minimal ground contact time (GCT). In addition, 400 m specialists possess a high anaerobic capacity and

buffering ability [26–28]. Finally, while short reaction times are essential for performance, it appears that at the elite level, this is not a limiting factor within each sex category [26]; nevertheless, at least at the elite level, men demonstrate significantly lower reaction times than women [29,31].

3.1.2. Middle Distance (800–3000 m)

Middle-distance events are perhaps the most complex and least understood running events. They typically last from <2 min to 10 min and are run at or above $\dot{V}O_{2\,Max}$ [22,26,27]. The actual and perceived levels of effort are often regarded as supra-maximal intense "anaerobic" efforts. However, research indicates that the aerobic energy contribution for even the 800 m run is at least 50% aerobic, with greater contributions for sub-elite runners, but it is likely predominantly aerobic by 1500 m and beyond [22,25,27,30]. Therefore, it should not be surprising that the training for these events is predominantly aerobic endurance volume [22]. The major determinants of performance for these events include an exceptional $\dot{V}O_{2\,Max}$ and the corresponding velocity ($v\dot{V}O_{2\,Max}$), as well as lactate threshold (LT) and the velocity at LT (vLT). There is also significant muscle force development and anaerobic (fast) glycolytic energy production, particularly for the 800 m run, and less for the 1500 and 3000 m events [26,27,30,32]. The latter factors make buffering capacity an important determinant of performance for these events [33]. Additionally, the development of speed and force in these events favors runners with greater Type II muscle fibers [22,26,27]. Finally, tactical aspects such as drafting have become more important in these and longer events [27].

3.2. Physiological Determinants of Long-Distance Running

Long-distance running events can be a relative term, but they typically involve events from 5000 m and up, where the aerobic energy system dominates and both central and peripheral factors are integrated to optimize performance. While one could argue that any activity lasting more than 3 min constitutes aerobic endurance activity, the determinants of performance for true endurance running rely almost solely on the aerobic system with minimal or virtually no significant "anaerobic" ATP contribution [27,34,35]. As described by Sandford and Stellingwurff [20], middle–long- and long-distance events are run at or below $\dot{V}O_{2\,Max}$ and at or above critical velocity, where aerobic ATP provides 85% or more of the energy. The general performance determinants of long-distance running are detailed elsewhere suffice it to say, regardless of distance, an adequately high $\dot{V}O_{2\,Max}$ is critical to performance, and within a homogeneous group of individuals, other factors such as the LT and running economy (RE) help determine the final performance velocity [33]. The relative importance of those other factors, however, varies somewhat based on the distance.

3.2.1. Middle–Long Distance (3000–10,000 m)

Performance in events lasting ~8 min or longer requires an exceptional $\dot{V}O_{2\,Max}$ and velocity at max ($v\dot{V}O_{2\,Max}$), as well as vLT, but also significant muscle force development and anaerobic (fast) glycolytic energy production, particular for the 3000 m run, and increasing less for 5000 m and 10,000 m events [26]. The latter factors make buffering capacity an important determinant of performance for events like the 3000 m run or steeplechase [33].

3.2.2. Long Distance (Half-Marathon and Marathon)

Like in middle–long-distance events, performance in events lasting an hour or longer requires a relatively high $\dot{V}O_{2\,Max}$. However, within a given cohort of athletes, $\dot{V}O_{2\,Max}$ accounts for just 59% of the variance [33], which ranges from 70 to 85 $mL.kg^{-1}.min^{-1}$ [36]. Assuming a sufficiently high $\dot{V}O_{2\,Max}$, vLT and RE are the predominant factors de-

termining performance, with thermoregulation being another factor as environmental temperature increases.

4. Running Performance During Adolescent Development

"Children are not small adults" is a common aphorism that holds true in sport, as well as in medicine. Throughout childhood, boys and girls grow in all aspects of their bodies while gaining an increased ability to use the bodies they develop. In this section, we highlight the most salient differences in performance between boys and girls and how biological development influences both sprint and endurance running across early and late adolescent development. For a summary of the major development changes across the lifespan, please see Table 1.

Table 1. Summary of major physical, physiological, and biomechanical changes across the lifespan for males and females engaged in regular formal training, as well as the relative impacts on running distance. Differences are based on the authors' interpretation and inferences drawn from the references presented in the paper, as well as professional experience. Adulthood = early and middle adulthood. ♂= male, ♀= female.

	Childhood		**Adolescence**		**Adulthood**		**Late Adulthood**	**Running Event Advantage**
	♂vs. ♀	**Δ**	**♂vs. ♀**	**Δ**	**♂vs. ♀**	**Δ**	**♂vs. ♀**	
Physical								
Height	>	♂↑ ♀↔	>>	↔	>>	↔	>>	Sprint, Mid, Long
Weight	>	↑	>>	↔	>>	↑	>>	
Body Fat	<	♂↓ ♀↑	<<	↔	<<	↑	<<	Sprint, Mid, Long
Muscle Mass	>	↑	>>	↔	>>	↓	>>	
Strength/Power	>	↑	>>	↔	>>	↓	>>	Sprint, Mid, Long
Heart Size	>	↑	>>	↔	>>	↔	>>	Sprint, Mid, Long
Higher SV								
Neurophysiological								
Type I/II Ratio	?	?	<	↔	<	↔	<	Long
$\dot{V}O_{2\,Max}$ (L/min)	>	↑	>	↔	>>	↓	>>	Mid, Long
Max Stroke Volume	>	↑	>	↔	>>	↔	>>	Mid, Long
Max Heart Rate	=	↑	=	↔	<	↓↓	<	Mid, Long
a-$vO_{2\,difference}$	=	↑	=	↔	=	↔	=	Mid, Long
Hb_{Mass}	=?	↑	>	↔	>	↔	>	Mid, Long
Lactate Threshold	=	↑	=	↔	=	↔	=	Mid, Long
Peak Lactate	=	↑	=	↔	=	↓	=	Sprint, Mid
Glycolytic Ability	=	↑	=	↔	=	↓	=	Sprint, Mid
Running Economy	=	↑?	=	↔	=	↔	=	Mid, Long
Biomechanical								
Stride Length	>	↑	>>	↔	>>	↓	>>	Sprint, Mid, Long
Stride Rate	=	↔	=	↔	=	↓	=	
Ground Contact Time	=?	↓	<	↔	<	↑	<	Sprint, Mid, Long
Ground Reaction Force	=?	↑	<	↔	<	↓	<	Sprint, Mid, Long

Small but significant running performance gaps appear as early as 5 yo between boys and girls [37–39] but remain stable until about age 13, before widening through early adulthood [40–43]. The underlying reasons for the performance gap at the younger ages are not fully understood, but evidence indicates that males experience an early "mini-puberty" that boosts growth after infancy [44], increasing skeletal muscle mass and strength [45,46] while reducing body fat [47]. It also likely accounts for the higher cardiac mass seen in boys [48–50]. These significant biological differences are likely enhanced by boys' propensity for greater physical play [51], which itself may widen the physical fitness gap between

boys and girls [52]. It is worth emphasizing, however, that the propensity to engage in physical activity (PA) is not merely a biological drive, as evidence indicates there is also a significant sociocultural and economic influence [53,54]. Nonetheless, the determinants of early sports success appear driven less by specific event determinants and more by developmental differences.

4.1. Childhood: It Is About the Fundamental Movement Skills

Sources vary on clear childhood developmental age delineations prior to AD, and there is a paucity of physiologic athletic data for Ch, particularly in girls. This is pertinent because there is a significant, albeit small to moderate, association between FMS competency and PA from early childhood into late AD [55–58]. Low FMS scores are associated with less physical activity and lower physical fitness [59]. Though it remains unclear whether competency begets PA or PA drives the development of FMS [56], research by Kokstejn et al. [57] noted that FMS was a significant mediator of the relationship between physical fitness and dribbling speed in early AD yo soccer players. Thus, greater development of specific fundamental movement skills at an earlier age would certainly provide advantages for sports dependent on those skills.

In addition to higher FMS scores, biomechanical and neuromuscular differences may also help separate high-performing children. For example, in a sample of nearly 2600 boys and girls aged 6–18 (i.e., Ch and AD), Kampmiller et al. [42] reported year-on-year increases in SL and speed in boys and girls until the age of 13, after which SL plateaus in girls but not boys, likely due to a plateau in girls' height; the latter plateau had also been reported earlier by Papaiakovou and colleagues [43]. Other important factors in running speed, like step frequency and GCT, appear more mixed. Thus, we can surmise that early success in sprint events is likely related to higher locomotor-related FMSs, which could influence neuromuscular coordination. Additionally, the largely linear changes in many determinants of sprinting, like height, underscore the importance of even short time horizons in developing children. This is borne out by the observation that the oldest children in a specific age category typically outperform their younger peers [60].

Research on endurance running in this age group up until at least puberty supports the notion that pre-pubertal children are generalists. Of note, good runners in this age group also display superior maximal running speed and run at a higher fraction of that speed than poor runners [61]. The consensus appears to be that children in this age group are highly aerobic, while possessing low glycolytic ability, either due to reduced enzyme availability and/or reduced recruitment of Type II muscle fibers [62–65]. From the available literature, a relatively high $\dot{V}O_{2\,Max}$ (>50 mL/kg/min) is typical in good runners, and the relative $\dot{V}O_{2\,Max}$ remains stable until at least puberty [65–67], but contrary to long-held views, it does appear trainable [67]. There remains a persistent dogma that children are significantly less economical than adults due to a shorter SL and compensatory higher SR, higher respiratory metabolic cost, greater reliance on fatty acids, and a lower stroke volume (SV) and cardiac output [64,68]. However, when scaled to body size and relative work intensities, the differences seem to disappear [69]. While evidence for improved economy with development or training is generally lacking, running velocity at LT improves in runners as young as age 5 [56,70]. Therefore, it appears that both central and peripheral factors may influence performance prior to puberty.

In summary, even in Ch, boys demonstrate a small but significant performance advantage over girls [37–39,71,72] that remains stable until puberty. Nonetheless, high-performing early childhood sprint and endurance athletes likely possess greater competency in FMS locomotor abilities, which encourage greater participation in sports. As generalists, children likely improve more in the sports they participate in. It is plausible

that small advantages in this age group from such participation lead to greater engagement in the activity, driving improvement—a positive feedback loop.

4.2. Adolescence: Sex, Puberty, and the Athletic Divide

Generally beginning around the age of 13 (EAD), the onset of puberty results in significant developmental changes in both sexes, but it also alters the potential for training adaptation in the body. Ignoring secondary sex characteristics, the most obvious changes include increases in height, weight, and limb dimensions; body composition also changes as muscle mass increases and fat mass decreases [44,45]. Like during infancy, cardiac mass also increases significantly more in boys than in girls [48–50]. These changes peak by the end of LAD [73]. Additionally, neuromuscular differences in strength, power, and agility between boys and girls are small prior to EAD but increase dramatically at puberty as boys gain neuromuscular abilities faster than girls, whose gains plateau towards LAD [74]. Less obvious are changes in viscera size and function, as well as in endocrine secretion. Therefore, performance potential can change significantly during this period.

As noted earlier [42,43], SL and speed increase in boys and girls until the age of 13, with boys showing an accelerated increase after 13. Stride frequency, however, dropped significantly in both boys and girls between ages 10 and 13 (EAD), coinciding with an increased GCT and flight time; most of these variable's trend back toward baseline after 13. This may be indicative of changes in neuromuscular coordination during sprinting, supporting the coaching and development of basic strength and technical aspects of sprinting during this period [43,73]. More recent work by Hsieh and colleagues [75] indicates that "elite" male and female junior sprinters may possess better auditory and sensorimotor processing systems, which result in improved start times. Nonetheless, the general determinants of sprint performance remain explosive power, leg length, and repeated sprint ability [76].

It appears that progression and performance differentiation for endurance events begin to mirror the same determinants observed in adult runners (outlined earlier). While there are several studies examining late adolescent middle-distance running up to 5000 m, there is a dearth of information beyond this distance. Regardless of sex differences, a relatively high $\dot{V}O_{2\,Max}$ is typical [34,77–79]. For events of 800 m to 1500 m, a high LT, or a similar submaximal lactate variable, and a high v$\dot{V}O_{2\,Max}$ were most commonly reported as determinants [34,70,77,79–82]. Additionally, more recent work by Bliss et al. [82] indicates that maximum heart rate (MHR) may also be a significant predictor of 800 m and 1500 m performance, while RE may influence events of 5000 m or longer [83,84].

Taken together, AD is characterized by a period of rapid development in both boys and girls that results in significant changes in both sprint and endurance running performance. During this period, males' height and weight growth accelerates, muscle mass generally increases, and body fat decreases; in contrast, females' height tends to plateau, while body fat increases more than muscle mass. Increased muscle mass relative to fat mass improves explosive power and sprint ability [76,85]. Additionally, higher male testosterone levels contribute to greater increases in heart size (i.e., stroke volume) and Hb_{mass} [86–88]. The latter change increases O_2 carrying capacity and the arterial-mix venous O_2 difference; both changes increase $\dot{V}O_{2\,Max}$. However, increases in estrogen in girls also result in unique metabolic changes that do afford women some advantages over men that are not as readily seen in shorter endurance events [50,89–91]. Hence, by early adulthood, men have significantly widened their performance advantage across all running events relative to women [92–96]. Drawing from several sources [97–104], Figures 1 and 2 offer graphical depictions of how select CBC values and sex hormones change across the lifespan.

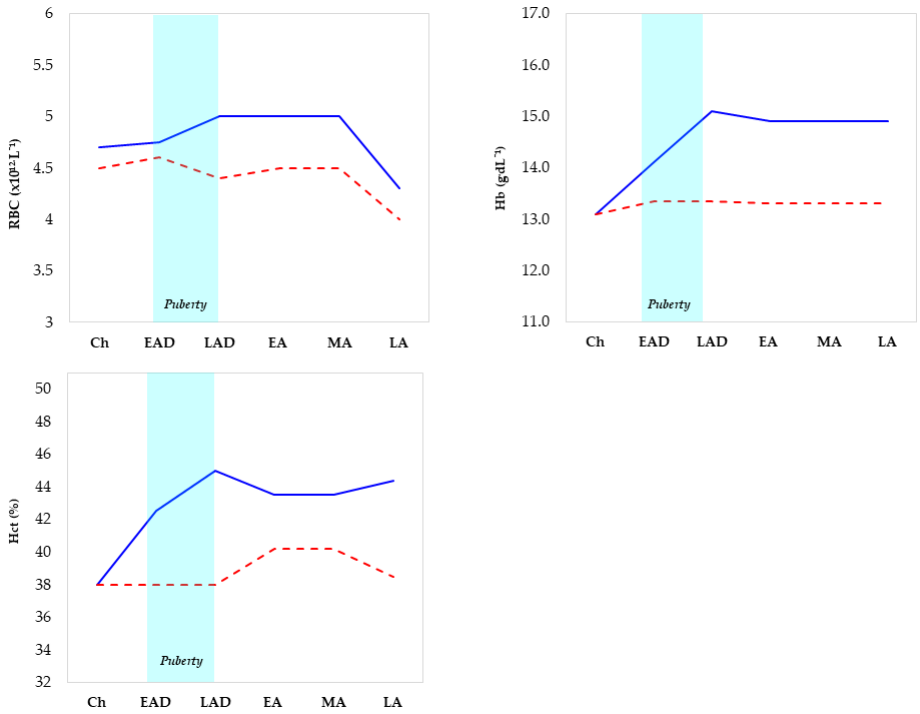


Figure 1. A graphic representation of changes in median values for RBC, Hb, and Hct for males (solid blue line) and females (dashed red line) across the lifespan. Data are an integration of several sources [101–104] for various age ranges to help contextualize how CBC values change across the developmental stages and relate to differences in endurance performance from youth to senescence. Y-axis limits are set near the ends of the normal reference ranges. Note: *AD is split into EAD and LAD to better depict pubertal changes (blue shade).*

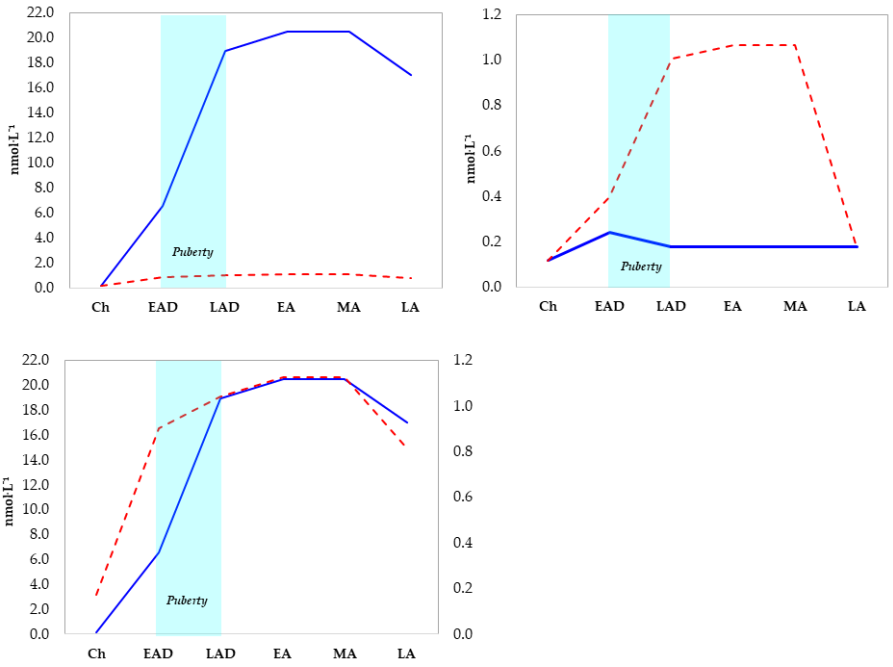


Figure 2. A graphic representation of changes in median values for absolute (**Top Left**) and relative (**Bottom Left**) total testosterone, and total estrogen (**Top Right**) for males (solid blue line) and females (dashed red line) across the lifespan. Data are an integration of several sources [97–100] for various age ranges to help contextualize how CBC values change across the developmental stages and relate to differences in endurance performance from youth to senescence. Note: *AD is split into EAD and LAD to better depict pubertal changes (blue shade).*

5. Adulthood: From Peak Performance to Accelerating Decline

5.1. Early Adulthood: Savoring the Fruits of Our Labor

During the peak (amateur to elite) adult years, athletes excel to some extent in one or more performance determinant, with elite athletes typically excelling in several. Prior research has also described the progression and age of peak performance, with explosive power/sprint and middle-distance athletes peaking near their mid-20s [9,105,106], whereas long-distance runners tend to peak at as late as 30 [92,106,107]. Moreover, Haugen et al. [105] noted that among elite athletes, those ranked in the top 10 show a greater rate of progression in the 5-year period prior to peak performance compared to lower-ranked runners across all disciplines. Finally, it does appear that most athletes are able to remain competitive for 5–10 years following their peak [105,107,108].

With physical maturity completed in the early 20s, continued improvements are generally related to refining key determinants within a specialty and peripheral adaptations. These changes allow many elite athletes, especially middle- and long-distance runners, to continue to improve for many years [33,94,106]. Finally, longer-duration events may lend themselves to experiential improvements in cognitive and more technical aspects of the event, like tactics, pacing, proper fueling, and perseverance [27,95,109–111].

As with sprint events, the rate of progression for men and women is roughly similar, and there remains a persistent performance gap, in part since men are taller (i.e., greater SL), heavier, and have significantly less body fat. The additional muscle mass in men allows them to generate more power, while men's larger hearts (i.e., higher SV and lower HR) [112], as well as their typically higher total blood volumes and red blood cell mass [96], increase $\dot{V}O_{2\,Max}$. In contrast, there appears to be little difference in LT relative to $\dot{V}O_{2\,Max}$ or RE [94]. This lack of difference coincides with contemporary research indicating that testosterone and estrogen are both uniquely beneficial to exercise adaptation, and both men and women can be expected to have similar performance improvements with training [87,90,91,96]. Nonetheless, it appears that the higher absolute $\dot{V}O_{2\,Max}$ and $v\dot{V}O_{2\,Max}$, resulting from various factors, allow men to run faster at a given SR with lower cardiovascular demand, giving them a greater capacity for cardiovascular output.

5.2. Middle to Late Adulthood: A Steady Then Accelerated Decline

As noted, peak performance for elite runners across disciplines is achieved at around age 26 or slightly later for marathon runners (EA), with women often reaching a greater peak age than men [105–108]. It also appears that across many sports and ability levels, relative peak performance can be maintained for a decade or more [92,105,107,113–118]. The first notable decline in performance occurs between ages 35 and 40—the beginning of MA—with a rate of decline that is similar between men and women [118–124]. This initial linear decline continues until the age of 70–80 years (LA) [118–120,122], when it accelerates into the final decades [122,124–127]. Differences in declination between sprint, middle-, and long-distance events are somewhat ambiguous, as some authors report greater declines in sprint events and others greater declines in endurance events [116,119,122,127], while a large study by Ganse et al. [119] indicated that declines were similar. One common weakness of these studies is their reliance on cross-sectional data, which typically show greater performance declines at any age than longitudinal studies. As case report data have suggested [117,128], longitudinal studies support the notion that continuous long-term training may slow but not stop aging-related decline [129,130].

The physiological mechanisms for aging-related declines in performance are discussed in detail elsewhere [123,127]. Studies clearly show a decrease in Type II fiber percentage with aging, but the impact of this change on performance is unclear. Some studies suggest it is inconsequential [123,127], whereas others show that the reduced Type II fiber percentage

is linked to lower muscle forces and increased GCT [131]. The latter data align with earlier work that shows peak blood lactate levels are lower in Masters sprinters [132], likely linked to reduced "anaerobic" enzyme activity in these athletes [133]. There do not appear to be differences between men and women in these regards. Lastly, there may be subtle but significant changes in kinematics with aging (e.g., reduced hip flexion), which may be a primary limitation related to changes in joint functionality or a secondary limitation related to reduced muscle strength or some combination of them [134].

Like sprinting and other sports, endurance running follows a similar pattern of decline, with small annual decrements beginning in MA [107,127,133,135], which minimally impact performance prior to age 50 [107,117,128,136]. Nonetheless, the available evidence indicates that decreased $\dot{V}O_{2\,Max}$ (Figure 3) is a major contributor to declines in endurance performance. This decrease is largely due to lower MHR and SV, as well as to smaller decreases in a-$vO_{2\,difference}$. There appears to be little or no change in RE or relative LT; however, the drop in $\dot{V}O_{2\,Max}$ results in a drop in absolute $v\dot{V}O_{2\,Max}$ and vLT/LT_{VO_2}. Finally, these losses appear to be similar in both men and women, and they are strongly related to diminished training volume [127,128,137].

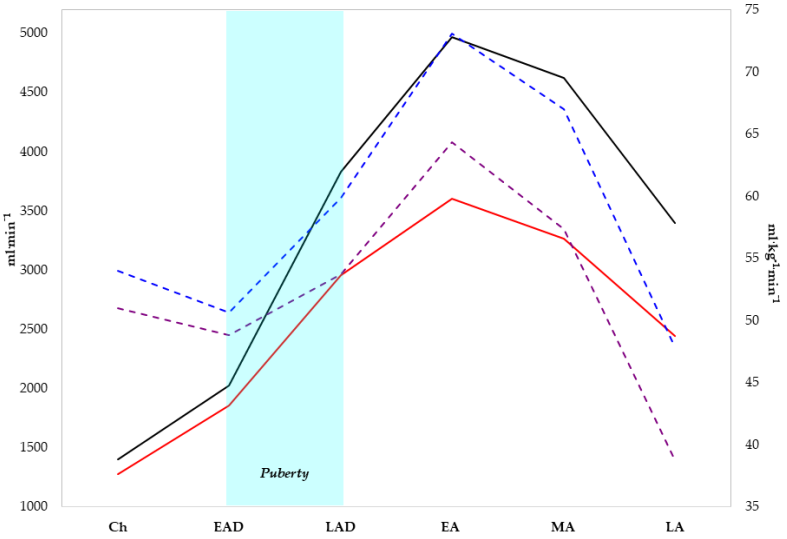


Figure 3. Graphic evolution of absolute $\dot{V}O_{2\,Max}$ for males (solid black) and females (solid red), and relative $\dot{V}O_{2\,Max}$ for males (dashed blue) and females (dashed purple). $\dot{V}O_{2\,Max}$ values were calculated using the Fick equation and data compiled from multiple sources and blood data presented in Figure 1. Values are intended to represent well-trained but not elite athletes. *Blue shade highlights puberty*.

6. Discussion

The purposes of this review were to merge and summarize the literature on our present understanding of the effects of sex and aging on running performance across the lifespan, as summarized in Table 1. Based on the available records [37,39] and the literature reviewed, we can conclude that boys (Ch) are on average 2.4% faster than girls in running events from 100 m to marathon distance, but the determinants of endurance performance appear similar between girls and boys, as does their relative progression in performance. However, puberty marks a significant divergence in progression and absolute differences, with boys jumping to a 5.3% advantage in EAD before holding a 12.3% advantage in the same events by LAD (see Figure 4A,B). Moreover, this margin remains throughout EA before widening across the remainder of the lifespan. However, the relative rate of progression to peak adult performance and then later regression into old age also appear to be similar between men and women until at least age 60. Nonetheless, there are many unanswered questions.

6.1. Adolescent Development Between Sexes More Consequential than Early Success

As mentioned, greater development of specific FMS at an earlier age provides advantages for sports dependent on those skills and is strongly related to engagement in PA and sports [55–58]. Different rates of growth and development early in life are typically the key differences between elite junior athletes and their peers [45,60]. However, continued sports participation is complex and influenced by both biological and socioeconomic factors [53,138]. Moreover, early sports success is poorly linked to success in adulthood [6–9,11,139], and early specialization has its own set of negative impacts [140]. Nonetheless, sport/event-specific performance determinants have become increasingly important in distinguishing top performers in LAD [6,9,105].

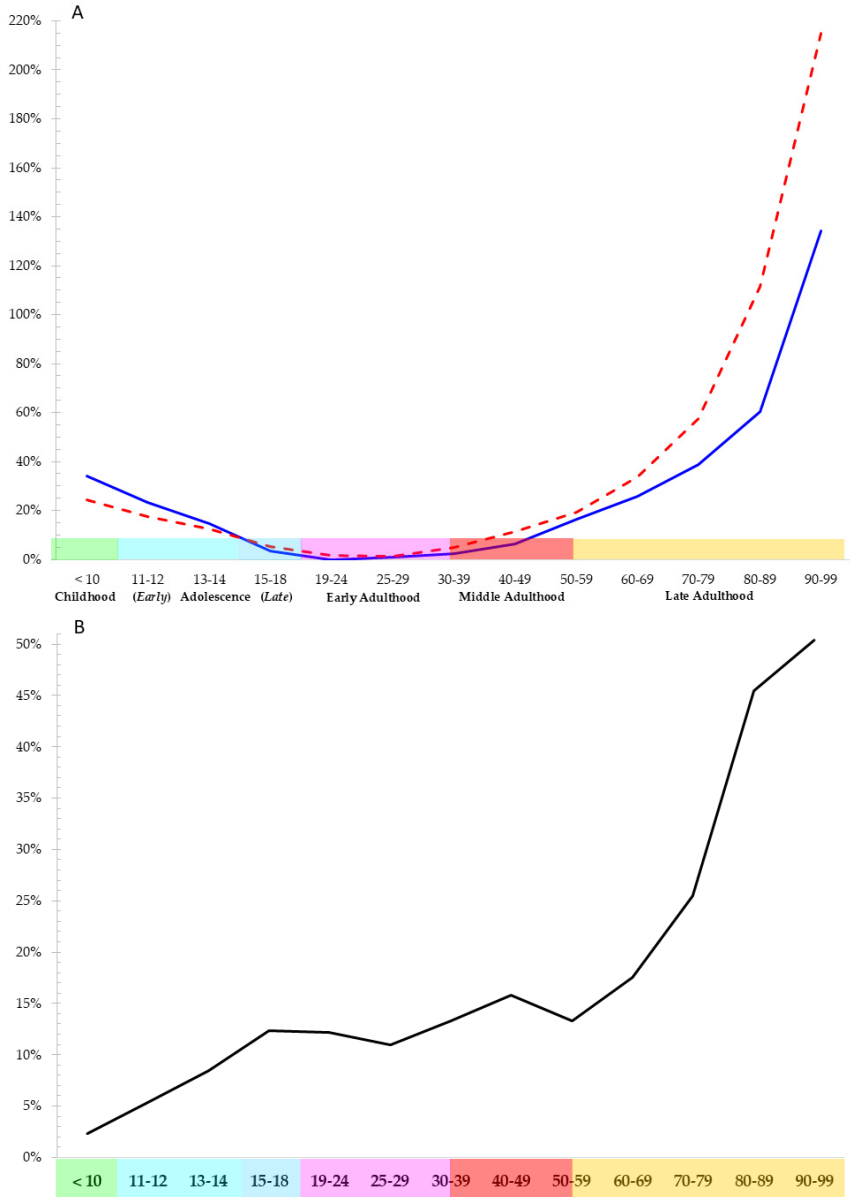


Figure 4. (**A**) Average relative difference in World Record Performance (i.e., 0% = WR) across *Sprint, Middle-, and Long-distance* running from Childhood through Late Adulthood. Males (solid blue) and females (dashed red) develop at similar rates and maintain performance levels similarly until about age 60, when woman appear to experience greater performance loss. All current records occur between 19 and 34 years. (**B**) Average relative sex differences across all running events from Ch to LA. Boys hold a 2.4 % advantage, increasing to over 11% throughout adulthood before increasing significantly into senescence. Note: *a positive % means males are faster* [37–39,141,142].

Sexual dimorphism is as consequential as development even in childhood, where small but consistent differences between boys and girls persist; boys exhibit lower locomotor and balance scores, while girls consistently score lower in object control [143–148]. However, as noted earlier, boys are generally taller, heavier, stronger, and have less body fat, even before puberty [44–47]. So, it should not be surprising that world records for boys (Ch) in sprint, middle-, and long-distance track events are faster than those for girls, with this average only widening after puberty and persisting throughout adulthood. These differences are so significant that by age 15 (LAD), many boys outpace elite women's world records (WRs), with men only slowing near the beginning of LA, after age 49 (Figure 5).

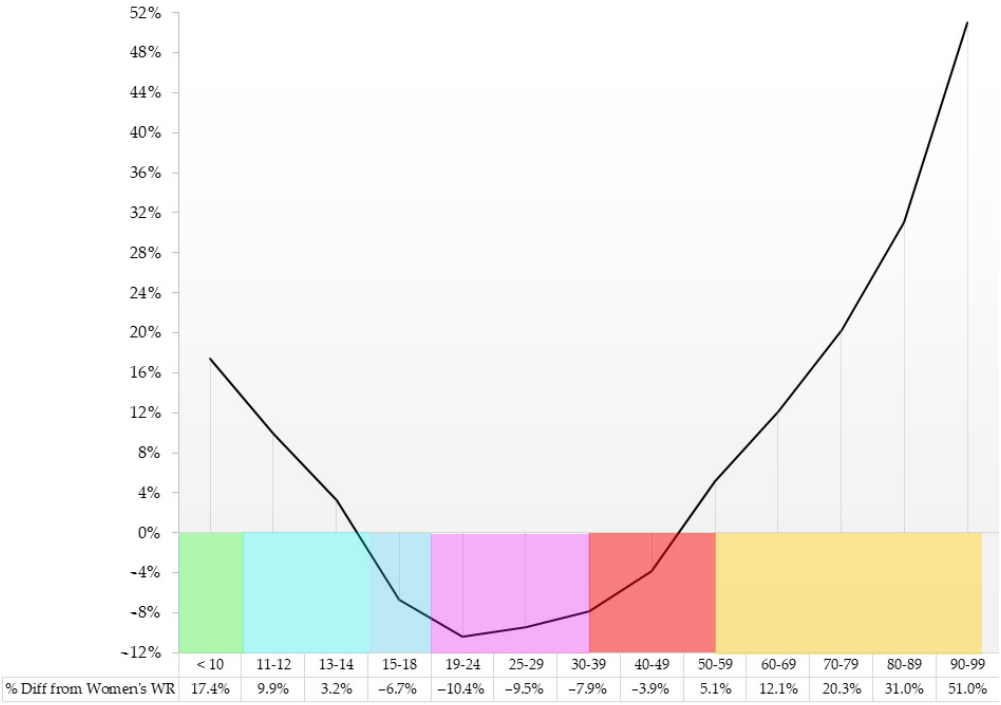


Figure 5. Comparison of male times relative to female world records across all running events discussed in the text. Data indicate that males are faster than female WRs from LAD (age 15 until age 49. Note: *negative percentages indicate males faster than women's WR times* [37–39,141,142].

Despite what is known about the fastest runners, more and/or updated research is needed across all adolescent groups. For instance, some long-held notions regarding children are that they are less trainable than adults, have lower glycolytic capacity, and run less economically [69,149–153]. These notions are challenged by more recent work. For example, early research [64,65,68,154] consistently showed that EAD runners were less economical than adults, whereas more recent data show that when children run at similar relative intensities, these differences largely disappear [69,155]. Thus, care should be taken when attempting to directly apply adult performance markers to children, or to women for that matter. Further, we need to sharpen our understanding of how both development and training progressions impact performance and be mindful that comparisons between children and adults are confounded by issues of scale related to size differences.

6.2. Peak Performance Differences Persist Between Men and Women, but Do Not Limit Progression

Based on this review and those of others [92,93,96,156] sex differences between men and women are real; however, with respect to trainability, rate of progression, and peak age, there appears to be little sex difference [105,156–159]. Moreover, estrogen appears to not only drive greater fat utilization in women but may also afford unique advantages in ultra-endurance events; the increased fat mobilization aids in cardiac remodeling [50,90,160]. This

has important implications for the recruitment, retention, and for example, development of women runners in all age groups. Additionally, greater emphasis should be placed on further elucidating the sex-related limiting factors for running determinants and potential training optimization for those factors.

6.3. Aging-Related Performance Decline Is Inevitable but Relatively Slow

One common theme across the literature is the impact that early physical activity and structured exercise training have on participation in sports and exercise throughout life. While research indicates that early specialization likely poses more harm than good [140,161], development of lifetime activities, like running, can dramatically improve one's long-term health trajectory [162]. However, from a more athletic viewpoint, middle to late adulthood offers a tremendous opportunity to continue to engage or even try new athletic pursuits. Advances in training and nutrition have allowed many athletes to remain highly competitive across age groups into the 40s or even 50s [5,107,117,128]. Moreover, evidence indicates that men and women are equally adaptive to training [91] and that older athletes have shown greater progressions in performance, allowing them to close the performance gap between younger and older runners [5].

As noted, sex differences persist between men and women; however, evidence indicates that the age-related decline in running events is similarly gradual between sexes until at least age 70, and then it likely follows a similar accelerated decline late in life. Taken together, both men and women can preserve much of their performance through significant exercise training, though the drop in training volume is often cited as a major instigator for drops in performance, with the most significant drop observed in $v\dot{V}O_{2\,Max}$ [123,127,128]. It is unclear what, if any, role training can play in further reducing the latter decline.

6.4. $\dot{V}O_{2\,Max}$ as the Ultimate Performance Variable

An interesting consideration in this review is the ultimate importance of $\dot{V}O_{2\,Max}$ on performance, particularly, but not exclusively in late adulthood. Like most exercise physiologists, the authors would contend that among a homogeneous well-trained group of runners, particularly elite runners, $\dot{V}O_{2\,Max}$ by itself is not the best predictor of performance; i.e., $\dot{V}O_{2\,Max}$ may place an individual into a particular tier of performers, but actual race performance is determined by knowledge, skills, and abilities. Importantly, most performance determinants are maintained or decline marginally with aging, except for $\dot{V}O_{2\,Max}$, which is a composite of several physiological variables (e.g., MHR, SV, a-$vO_{2\,Difference}$), thus lowering our ultimate aerobic ceiling late in life. However, across the lifespan, $\dot{V}O_{2\,Max}$ may also influence all running events. The rationale here comes from two directions.

First, for all but the shortest events (i.e., 100 or 200 m), energy system use, along with many performance determinants, is based on young, near-elite, or world-class runners. However, even the best age-group running times are 10–30% slower in these events between 10 and 59 yo. Therefore, caution must be exercised when considering energy system demands, which inevitably shift toward greater aerobic energy production. Moreover, Ferguson and colleagues have recently proposed and supported the hypothesis that even sprint athletes require greater development of the aerobic system [163,164]. With this in mind, we can revisit Figure 4 now envisioning that the progression and ultimate regression in running performance across the lifespan may be most reliant on $\dot{V}O_{2\,Max}$ for developing and preserving lifelong running in most events.

6.5. Limitations and Future Directions

This review is not without its limitations. First, the authors have presented a broad review of the literature using an extensive but not systematic review approach. Our main

objective was to summarize the role that developmental changes play in running performance across the lifespan for men and women. Such a broad review is not immune to potential biases in the literature search or topic focus. A second limitation, as noted earlier, is the broad focus of this topic. Thus, this paper is primarily intended to be a resource summarizing what is known and the major sources used to support those assertions. We hope our review will fuel future research. As noted by Armstrong and colleagues [150,155,165], new and expanded research in pediatrics is overdue. New tools allow us to elucidate areas of performance once unattainable. Both physiological and cardiac data are all but absent for early adolescent girls, and little is known about their buffering capacity across AD. It is also unclear how changes in endocrine function, particularly late in life, affect the development or decline in the performance changes reviewed in the literature. Finally, while several recent analyses have focused on certain aspects of running record performance for both elite and age-group runners, a comprehensive analysis is needed to better understand the developmental progression and regression of running performance across the lifespan.

7. Conclusions

In conclusion, the authors note that while significant sex differences are observed during childhood and widen to the advantage of males by adulthood, males and females appear to rely on the same performance determinants specific to their running events. Except during puberty, when boys show an accelerated performance enhancement, both men and women appear to progress similarly to peak performance, maintaining a high-performance level until about age 60, before declining at a more accelerated rate.

Author Contributions: Conceptualization, C.R.H.; methodology, C.R.H. and T.C.S.; formal analysis, C.R.H. and T.C.S.; investigation, C.R.H. and T.C.S.; data curation, C.R.H.; writing—original draft preparation, C.R.H. and T.C.S.; writing—review and editing, C.R.H. and T.C.S.; visualization, C.R.H. and T.C.S.; project administration, C.R.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

AD	Adolescence
AG	Age-group amateur athletes
ATP	Adenosine triphosphate
a-v$O_{2\ difference}$	Arterio-venous oxygen difference
Ch	Childhood
CO	Cardiac output
EA	Early adulthood
FMS	Fundamental movement skill
Hb_{Mass}	Hemoglobin mass of the blood
Hct	Hematocrit
LT	Lactate threshold; used broadly in the paper to refer to some blood lactate-based measure
GCT	Ground contact time
GRF	Ground reaction force

LA	Late adulthood
MA	Middle adulthood
MCV	Mean corpuscle volume
MHR	Maximum heart rate
PA	Physical activity
PCr	Creatine phosphate
RBC	Red blood cell
RE	Running economy
SR	Step rate as steps per minute
SL	Stride length
SV	Stroke volume
vLT	Velocity at lactate threshold
$\dot{V}O_{2\,LT}$	Oxygen consumption at lactate threshold
$\dot{V}O_{2\,Max}$	Maximal oxygen consumption
$v\dot{V}O_{2\,Max}$	Velocity at maximal oxygen consumption
WBC	White blood cell
WR	World record
YO	Years old

References

1. Mattson, M.P. Evolutionary Aspects of Human Exercise—Born to Run Purposefully. *Ageing Res. Rev.* **2012**, *11*, 347–352. [CrossRef] [PubMed]
2. Bramble, D.M.; Lieberman, D.E. Endurance Running and the Evolution of Homo. *Nature* **2004**, *432*, 345–352. [CrossRef] [PubMed]
3. Rizzo, N. 120+ Running Statistics 2021/2022 [Research Review] 2023. Available online: https://runrepeat.com/running-statistics (accessed on 21 March 2025).
4. Lathan, S.R. A History of Jogging and Running—The Boom of the 1970s. *Bayl. Univ. Med. Cent. Proc.* **2023**, *36*, 775–777. [CrossRef]
5. Akkari, A.; Machin, D.; Tanaka, H. Greater Progression of Athletic Performance in Older Masters Athletes. *Age Ageing* **2015**, *44*, 683–686. [CrossRef] [PubMed]
6. Brustio, P.R.; Stival, M.; Cardinale, M.; Mulasso, A.; Rainoldi, A.; Boccia, G. Performance Pathways in Elite Middle-and Long-Distance Track and Field Athletes: The Influence of a Successful Youth. *J. Sci. Med. Sport.* **2024**, *27*, 654–659. [CrossRef]
7. Agudo-Ortega, A.; Gonzalez-Rave, J.M.; Salinero, J.J. Early Success Is Not a Prerequisite for Success at the Adult Age in Spanish Sprinters. *J. Hum. Kinet.* **2023**, *89*, 139. [CrossRef]
8. Bezuglov, E.; Emanov, A.; Waśkiewicz, Z.; Semeniuk, N.; Butovsky, M.; Shoshorina, M.; Baranova, D.; Volodina, K.; Morgans, R. Successful Young Athletes Have Low Probability of Being Ranked among the Best Senior Athletes, but This Is Higher When Compared to Their Less Successful Peers. *Front. Psychol.* **2022**, *13*, 869637. [CrossRef] [PubMed]
9. Boccia, G.; Cardinale, M.; Brustio, P.R. World-Class Sprinters' Careers: Early Success Does Not Guarantee Success at Adult Age. *Int. J. Sports Physiol. Perform.* **2020**, *16*, 367–374. [CrossRef]
10. Boccia, G.; Moisè, P.; Franceseschi, A.; Trova, F.; Panero, D.; La Torre, A.; Rainoldi, A.; Schena, F.; Cardinale, M. Correction: Career Performance Trajectories in Track and Field Jumping Events from Youth to Senior Success: The Importance of Learning and Development. *PLoS ONE* **2017**, *12*, e0178662. [CrossRef]
11. Güllich, A.; Barth, M.; Macnamara, B.N.; Hambrick, D.Z. Quantifying the Extent to Which Successful Juniors and Successful Seniors Are Two Disparate Populations: A Systematic Review and Synthesis of Findings. *Sports Med.* **2023**, *53*, 1201–1217. [CrossRef]
12. Casado, A.; Hanley, B.; Santos-Concejero, J.; Ruiz-Pérez, L.M. World-Class Long-Distance Running Performances Are Best Predicted by Volume of Easy Runs and Deliberate Practice of Short-Interval and Tempo Runs. *J. Strength. Cond. Res.* **2021**, *35*, 2525–2531. [CrossRef]
13. Senefeld, J.W.; Haischer, M.H.; Jones, A.M.; Wiggins, C.C.; Beilfuss, R.; Joyner, M.J.; Hunter, S.K. Technological Advances in Elite Marathon Performance. *J. Appl. Physiol.* **2021**, *130*, 2002–2008. [CrossRef]
14. Tanaka, H.; Seals, D.R. Scientific Writing in Physiology: Confused/Misused Terms and Phrases. *J. Appl. Physiol.* **2024**, *136*, 401–407. [CrossRef]
15. Tanaka, H.; Tarumi, T.; Rittweger, J. Aging and Physiological Lessons from Master Athletes. In *Comprehensive Physiology*; Terjung, R., Ed.; Wiley & Sons: Hoboken, NJ, USA, 2019; pp. 261–296. ISBN 978-0-470-65071-4.
16. Sawyer, S.M.; Azzopardi, P.S.; Wickremarathne, D.; Patton, G.C. The Age of Adolescence. *Lancet Child. Adolesc. Health* **2018**, *2*, 223–228. [CrossRef] [PubMed]

17. Blum, R.W.; Astone, N.M.; Decker, M.R.; Mouli, V.C. A Conceptual Framework for Early Adolescence: A Platform for Research. *Int. J. Adolesc. Med. Health* **2014**, *26*, 321–331. [CrossRef] [PubMed]
18. Balasundaram, P.; Avulakunta, I.D. Human Growth and Development. In *StatPearls*; StatPearls Publishing: Treasure Island, FL, USA, 2025.
19. Newell, K.M. What Are Fundamental Motor Skills and What Is Fundamental About Them? *J. Mot. Learn. Dev.* **2020**, *8*, 280–314. [CrossRef]
20. Sandford, G.N.; Stellingwerff, T. "Question Your Categories": The Misunderstood Complexity of Middle-Distance Running Profiles with Implications for Research Methods and Application. *Front. Sports Act. Living* **2019**, *1*, 28. [CrossRef]
21. Our Sport 2025. World Athletics. Available online: https://worldathletics.org/our-sport (accessed on 23 January 2025).
22. Haugen, T.; Sandbakk, Ø.; Enoksen, E.; Seiler, S.; Tønnessen, E. Crossing the Golden Training Divide: The Science and Practice of Training World-Class 800- and 1500-m Runners. *Sports Med.* **2021**, *51*, 1835–1854. [CrossRef]
23. Majumdar, A.S.; Robergs, R.A. The Science of Speed: Determinants of Performance in the 100 m Sprint. *Int. J. Sports Sci. Coach.* **2011**, *6*, 479–493. [CrossRef]
24. Duffield, R.; Dawson, B.; Goodman, C. Energy System Contribution to 100-m and 200-m Track Running Events. *J. Sci. Med. Sport.* **2004**, *7*, 302–313. [CrossRef]
25. Duffield, R.; Dawson, B.; Goodman, C. Energy System Contribution to 400-Metre and 800-Metre Track Running. *J. Sports Sci.* **2005**, *23*, 299–307. [CrossRef]
26. Thompson, M.A. Physiological and Biomechanical Mechanisms of Distance Specific Human Running Performance. *Integr. Comp. Biol.* **2017**, *57*, 293–300. [CrossRef] [PubMed]
27. Stellingwerff, T.; Bovim, I.M.; Whitfield, J. Contemporary Nutrition Interventions to Optimize Performance in Middle-Distance Runners. *Int. J. Sport. Nutr. Exerc. Metab.* **2019**, *29*, 106–116. [CrossRef] [PubMed]
28. Weyand, P.G.; Sandell, R.F.; Prime, D.N.L.; Bundle, M.W. The Biological Limits to Running Speed Are Imposed from the Ground Up. *J. Appl. Physiol.* **2010**, *108*, 950–961. [CrossRef]
29. Lipps, D.B.; Galecki, A.T.; Ashton-Miller, J.A. On the Implications of a Sex Difference in the Reaction Times of Sprinters at the Beijing Olympics. *PLoS ONE* **2011**, *6*, e26141. [CrossRef] [PubMed]
30. Duffield, R.; Dawson, B.; Goodman, C. Energy System Contribution to 1500- and 3000-Metre Track Running. *J. Sports Sci.* **2005**, *23*, 993–1002. [CrossRef]
31. Tønnessen, E.; Haugen, T.; Shalfawi, S.A.I. Reaction Time Aspects of Elite Sprinters in Athletic World Championships. *J. Strength Cond. Res.* **2013**, *27*, 885–892. [CrossRef]
32. Rabadán, M.; Díaz, V.; Calderón, F.J.; Benito, P.J.; Peinado, A.B.; Maffulli, N. Physiological Determinants of Speciality of Elite Middle- and Long-Distance Runners. *J. Sports Sci.* **2011**, *29*, 975–982. [CrossRef]
33. Joyner, M.J.; Coyle, E.F. Endurance Exercise Performance: The Physiology of Champions: Factors That Make Champions. *J. Physiol.* **2008**, *586*, 35–44. [CrossRef]
34. de Souza, K.M.; Vieira, G.; Baldi, M.F.; Guglielmo, L.G.A.; de Lucas, R.D.; Denadai, B.S. Physiological and Neuromuscular Variables Associated to Aerobic Performance in Endurance Runners: Effects of the Event Distance. *Rev. Bras. De. Med. Do Esporte* **2011**, *17*, 40–44.
35. Lacour, J.R.; Padilla-Magunacelaya, S.; Bartholomy, J.C.; Dormois, D. The Energetics of Middle-Distance Running. *Europ. J. Appl. Physiol.* **1990**, *60*, 38–43. [CrossRef]
36. Venturini, E.; Giallauria, F. Factors Influencing Running Performance During a Marathon: Breaking the 2-h Barrier. *Front. Cardiovasc. Med.* **2022**, *9*, 856875. [CrossRef]
37. INTERNATIONAL AGE RECORDS. Available online: http://age-records.125mb.com/ (accessed on 3 February 2025).
38. USA Track & Field | USATF National Junior Olympic Track & Field Championships Records. Available online: https://www.usatf.org/resources/statistics/records/championship-meet-records/usatf-national-junior-olympic-track-field-champion (accessed on 3 February 2025).
39. World Single Age Records. Available online: https://arrs.run/SARec.htm (accessed on 3 February 2025).
40. Atkinson, G.; Peacock, O.; Passfield, L. Variable versus Constant Power Strategies during Cycling Time-Trials: Prediction of Time Savings Using an up-to-Date Mathematical Model. *J. Sports Sci.* **2007**, *25*, 1001–1009. [CrossRef] [PubMed]
41. Brown, S.; Saunders, L.; Krause, J. Racial Disparities in Depression and Life Satisfaction After Spinal Cord Injury: A Mediational Model. *Top. Spinal Cord. Inj. Rehabil.* **2012**, *18*, 232–240. [CrossRef] [PubMed]
42. Kampmiller, T.; Vanderka, M.; Šelinger, P.; Šelingerová, M.; Čierna, D. KInematic Parameters of the Running Stride in 7-To 18-Year-Old Youth. *Kinesiol. Slov.* **2011**, *17*, 1.
43. Papaiakovou, G.; Giannakos, A.; Michailidis, C.; Patikas, D.; Bassa, E.; Kalopisis, V.; Anthrakidis, N.; Kotzamanidis, C. The Effect of Chronological Age and Gender on the Development of Sprint Performance during Childhood and Puberty. *J. Strength Cond. Res.* **2009**, *23*, 2568–2573. [CrossRef] [PubMed]

44. Kiviranta, P.; Kuiri-Hänninen, T.; Saari, A.; Lamidi, M.-L.; Dunkel, L.; Sankilampi, U. Transient Postnatal Gonadal Activation and Growth Velocity in Infancy. *Pediatrics* **2016**, *138*, e20153561. [CrossRef]
45. Malina, R.M.; Rogol, A.D.; Cumming, S.P.; Coelho E Silva, M.J.; Figueiredo, A.J. Biological Maturation of Youth Athletes: Assessment and Implications. *Br. J. Sports Med.* **2015**, *49*, 852–859. [CrossRef]
46. Malina, R.M.; Bouchard, C.; Beunen, G. Human Growth: Selected Aspects of Current Research on Well-Nourished Children. *Annu. Rev. Anthropol.* **1988**, *17*, 187–219. [CrossRef]
47. Davis, S.M.; Kaar, J.L.; Ringham, B.M.; Hockett, C.W.; Glueck, D.H.; Dabelea, D. Sex Differences in Infant Body Composition Emerge in the First 5 Months of Life. *J. Pediatr. Endocrinol. Metab.* **2019**, *32*, 1235–1239. [CrossRef]
48. De Simone, G.; Devereux, R.B.; Daniels, S.R.; Meyer, R.A. Gender Differences in Left Ventricular Growth. *Hypertension* **1995**, *26*, 979–983. [CrossRef] [PubMed]
49. St Pierre, S.R.; Peirlinck, M.; Kuhl, E. Sex Matters: A Comprehensive Comparison of Female and Male Hearts. *Front. Physiol.* **2022**, *13*, 831179. [CrossRef]
50. Foryst-Ludwig, A.; Kintscher, U. Sex Differences in Exercise-Induced Cardiac Hypertrophy. *Pflug. Arch. Eur. J. Physiol.* **2013**, *465*, 731–737. [CrossRef] [PubMed]
51. Belcher, B.R.; Berrigan, D.; Dodd, K.W.; Emken, B.A.; Chou, C.-P.; Spruijt-Metz, D. Physical Activity in US Youth: Effect of Race/Ethnicity, Age, Gender, and Weight Status. *Med. Sci. Sports Exerc.* **2010**, *42*, 2211–2221. [CrossRef]
52. Pate, R.R. Associations Between Physical Activity and Physical Fitness in American Children. *Arch. Pediatr. Adolesc. Med.* **1990**, *144*, 1123. [CrossRef]
53. Lindquist, C.H.; Reynolds, K.D.; Goran, M.I. Sociocultural Determinants of Physical Activity among Children. *Prev. Med.* **1999**, *29*, 305–312. [CrossRef]
54. Gosselin, V.; Leone, M.; Laberge, S. Socioeconomic and Gender-Based Disparities in the Motor Competence of School-Age Children. *J. Sports Sci.* **2021**, *39*, 341–350. [CrossRef]
55. Wu, H.; Eungpinichpong, W.; Ruan, H.; Zhang, X.; Dong, X. Relationship between Motor Fitness, Fundamental Movement Skills, and Quality of Movement Patterns in Primary School Children. *PLoS ONE* **2021**, *16*, e0237760. [CrossRef]
56. Jones, A.M.; Carter, H. The Effect of Endurance Training on Parameters of Aerobic Fitness. *Sports Med.* **2000**, *29*, 373–386. [CrossRef]
57. Kokstejn, J.; Musalek, M.; Wolanski, P.; Murawska-Cialowicz, E.; Stastny, P. Fundamental Motor Skills Mediate the Relationship Between Physical Fitness and Soccer-Specific Motor Skills in Young Soccer Players. *Front. Physiol.* **2019**, *10*, 596. [CrossRef]
58. Holfelder, B.; Schott, N. Relationship of Fundamental Movement Skills and Physical Activity in Children and Adolescents: A Systematic Review. *Psychol. Sport. Exerc.* **2014**, *15*, 382–391. [CrossRef]
59. Liu, C.; Cao, Y.; Zhang, Z.; Gao, R.; Qu, G. Correlation of Fundamental Movement Skills with Health-Related Fitness Elements in Children and Adolescents: A Systematic Review. *Front. Public. Health* **2023**, *11*, 9258. [CrossRef]
60. Gundersen, H.; Harris, A.; Grendstad, H.; Kristoffersen, M.; Guttormsen, A.; Dalen, T.; Rygh, C.B. Performance in Youth Track and Field Is Associated with Birth Quartile. A Register-Based Study among Athletes in Norway from 10 Years to Senior Level. *PLoS ONE* **2022**, *17*, e0273472. [CrossRef] [PubMed]
61. Krahenbuhl, G.S.; Pangrazi, R.P.; Chomokos, E.A. Aerobic Responses of Young Boys to Submaximal Running. *Res. Quarterly Am. Alliance Health Phys. Educ. Recreat. Danc.* **1979**, *50*, 413–421. [CrossRef]
62. Van Praagh, E.; Dor, E. Short-Term Muscle Power During Growth and Maturation. *Sports Med.* **2002**, *32*, 701–728. [CrossRef]
63. Prasad, N. The Relationship Between Aerobic and Anaerobic Exercise Capacities in Pre-Pubertal Children. Ph.D. Thesis, University of British Columbia, Vancouver, BC, Canada, 2009. [CrossRef]
64. Rowland, T.W. Developmental Aspects of Physiological Function Relating to Aerobic Exercise in Children. *Sports Med.* **1990**, *10*, 255–266. [CrossRef] [PubMed]
65. Krahenbuhl, G.S.; SKINNER, J.S.; KOHRT, W.M. Developmental Aspects of Maximal Aerobic Power in Children. *Exerc. Sport. Sci. Rev.* **1985**, *13*, 503–538. [CrossRef]
66. Rowland, T. Oxygen Uptake and Endurance Fitness in Children, Revisited. *Pediatr. Exerc. Sci.* **2013**, *25*, 4. [CrossRef]
67. Baxter-Jones, A.D.G.; Maffulli, N. Endurance in Young Athletes: It Can Be Trained. *Br. J. Sports Med.* **2003**, *37*, 96–97. [CrossRef]
68. Krahenbuhl, G.S.; Williams, T.J. Running Economy: Changes with Age during Childhood and Adolescence. *Med. Sci. Sports Exerc.* **1992**, *24*, 462–466. [CrossRef]
69. Rowland, T. Inferior Exercise Economy in Children: Perpetuating a Myth? *Pediatr. Exerc. Sci.* **2012**, *24*, 501–506. [CrossRef] [PubMed]
70. Tanaka, H.; Shindo, M. Running Velocity at Blood Lactate Threshold of Boys Aged 6–15 Years Compared with Untrained and Trained Young Males. *Int. J. Sports Med.* **1985**, *06*, 90–94. [CrossRef]
71. Atkinson, M.; James, J.; Quinn, M.; Senefeld, J.; Hunter, S. Sex Differences in Track and Field Elite Youth 2024. Available online: https://sportrxiv.org/index.php/server/preprint/view/324/774 (accessed on 1 March 2025).

72. Brown, G.A.; Shaw, B.S.; Shaw, I. Sex-based Differences in Track Running Distances of 100, 200, 400, 800, and 1500m in the 8 and under and 9–10-year-old Age Groups. *Eur. J. Sport. Sci.* **2024**, *24*, 217–225. [CrossRef]
73. Aerenhouts, D.; Delecluse, C.; Hagman, F.; Taeymans, J.; Debaere, S.; Van Gheluwe, B.; Clarys, P. Comparison of Anthropometric Characteristics and Sprint Start Performance between Elite Adolescent and Adult Sprint Athletes. *Eur. J. Sport. Sci.* **2012**, *12*, 9–15. [CrossRef]
74. Eisenmann, J.; Malina, R. Age- and Sex-Associated Variation in Neuromuscular Capacities of Adolescent Distance Runners. *J. Sports Sci.* **2003**, *21*, 551–557. [CrossRef]
75. Hsieh, Y.-L.; Yen, S.-W.; Chang, C.-M.; Li, W.-C.; Yang, N.-P.; Chen, H.-Y. Sensorimotor Processing in Elite and Sub-Elite Adolescent Sprinters during Sprint Starts: An Electrophysiological Study. *Sports* **2024**, *12*, 222. [CrossRef]
76. Alves, D.L.; Castro, P.H.C.; Freitas, J.V.; De-Oliveira, F.R.; Lima, J.R.P.; Cruz, R. What Variables Determine Sprint Performance in Young Athletes? *Sci. Sports* **2021**, *36*, e87–e94. [CrossRef]
77. Fernhall, B.; Kohrt, W.; Burkett, L.N.; Walters, S. Relationship between the Lactate Threshold and Cross-Country Run Performance in High School Male and Female Runners. *Pediatr. Exerc. Sci.* **1996**, *8*, 37–47. [CrossRef]
78. Nudel, D.B.; Hassett, I.; Gurian, A.; Diamant, S.; Weinhouse, E.; Gootman, N. Young Long Distance Runners: Physiological and Psychological Characteristics. *Clin. Pediatr.* **1989**, *28*, 500–505. [CrossRef]
79. Coelho e Silva, M.J. *Youth Sports: Growth, Maturation and Talent*; Investigação; Coimbra University Press: Outubro, Portugal, 2010; ISBN 978-989-26-0005-5.
80. Cole, A.S.; Woodruff, M.E.; Horn, M.P.; Mahon, A.D. Strength, Power, and Aerobic Exercise Correlates of 5-Km Cross-Country Running Performance in Adolescent Runners. *Pediatr. Exerc. Sci.* **2006**, *18*, 374–384. [CrossRef]
81. Ali Almarwaey, O.; Mark Jones, A.; Tolfrey, K. Physiological Correlates with Endurance Running Performance in Trained Adolescents. *Med. Sci. Sports Exerc.* **2003**, *35*, 480–487. [CrossRef]
82. Bliss, A.; Waldron, M.; Maxwell, N. Predicting Middle-distance Track and Cross-country Performances of National and International Level Adolescent Runners. *Eur. J. Sport. Sci.* **2022**, *22*, 305–313. [CrossRef]
83. Dellagrana, R.A.; Guglielmo, L.G.; Santos, B.V.; Hernandez, S.G.; da Silva, S.G.; de Campos, W. Physiological, Anthropometric, Strength, and Muscle Power Characteristics Correlates with Running Performance in Young Runners. *J. Strength. Cond. Res.* **2015**, *29*, 1584–1591. [CrossRef] [PubMed]
84. Cunningham, L.N. Physiologic Comparison of Adolescent Female and Male Cross-Country Runners. *Pediatr. Exerc. Sci.* **1990**, *2*, 313–321. [CrossRef] [PubMed]
85. Bustamante-Garrido, A.; Aedo-Muñoz, E.; Brito, C.; Silva-Esparza, D.; Pérez-Contreras, J.; Izquierdo-Redin, M.; Cerda-Kohler, H. Anthropometric and Mechanical Factors Determining Sprint in Young Soccer Players: A Brief Report. *Front. Sports Act. Living* **2024**, *6*, 1480973. [CrossRef]
86. Janz, K.F.; Dawson, J.D.; Mahoney, L.T. Predicting Heart Growth During Puberty: The Muscatine Study. *Pediatrics* **2000**, *105*, e63. [CrossRef] [PubMed]
87. Forså, M.I.; Bjerring, A.W.; Haugaa, K.H.; Smedsrud, M.K.; Sarvari, S.I.; Landgraff, H.W.; Hallén, J.; Edvardsen, T. Young Athlete's Growing Heart: Sex Differences in Cardiac Adaptation to Exercise Training during Adolescence. *Open Heart* **2023**, *10*, e002155. [CrossRef]
88. Weberruß, H.; Engl, T.; Baumgartner, L.; Mühlbauer, F.; Shehu, N.; Oberhoffer-Fritz, R. Cardiac Structure and Function in Junior Athletes: A Systematic Review of Echocardiographic Studies. *Rev. Cardiovasc. Med.* **2022**, *23*, 129. [CrossRef]
89. Chidi-Ogbolu, N.; Baar, K. Effect of Estrogen on Musculoskeletal Performance and Injury Risk. *Front. Physiol.* **2019**, *9*, 1834. [CrossRef]
90. Collado-Boira, E.; Baliño, P.; Boldo-Roda, A.; Martínez-Navarro, I.; Hernando, B.; Recacha-Ponce, P.; Hernando, C.; Muriach, M. Influence of Female Sex Hormones on Ultra-Running Performance and Post-Race Recovery: Role of Testosterone. *Int. J. Environ. Res. Public Health* **2021**, *18*, 10403. [CrossRef]
91. Lowe, D.A.; Baltgalvis, K.A.; Greising, S.M. Mechanisms Behind Estrogen's Beneficial Effect on Muscle Strength in Females. *Exerc. Sport. Sci. Rev.* **2010**, *38*, 61–67. [CrossRef] [PubMed]
92. Roy, T.K.; Joyner, M.J.; Senefeld, J.W.; Wiggins, C.C.; Secomb, T.W. An Empirical Model for World Record Running Speeds with Distance, Age, and Sex: Anaerobic and Aerobic Contributions to Performance. *J. Appl. Physiol.* **2024**, *137*, 357–363. [CrossRef]
93. Joyner, M.J.; Hunter, S.K.; Senefeld, J.W. Evidence on Sex Differences in Sports Performance. *J. Appl. Physiol.* **2025**, *138*, 274–281. [CrossRef]
94. Joyner, M.J. Physiological Limits to Endurance Exercise Performance: Influence of Sex: Sex, Exercise and Elite Endurance Performance. *J. Physiol.* **2017**, *595*, 2949–2954. [CrossRef] [PubMed]
95. Besson, T.; Macchi, R.; Rossi, J.; Morio, C.Y.M.; Kunimasa, Y.; Nicol, C.; Vercruyssen, F.; Millet, G.Y. Sex Differences in Endurance Running. *Sports Med.* **2022**, *52*, 1235–1257. [CrossRef]
96. Hilton, E.N.; Lundberg, T.R. Correction to: Transgender Women in the Female Category of Sport: Perspectives on Testosterone Suppression and Performance Advantage. *Sports Med.* **2021**, *51*, 2235. [CrossRef] [PubMed]

97. Fisher, D. Endocrinology: Test Selection and Interpretation; Quest Diagnostics. 2007. Available online: https://specialtytesting.labcorp.com/sites/default/files/2021-07/L5167-0421-18%20Endocrine%20Expected%20Values_0.pdf (accessed on 23 February 2025).
98. Cappola, A.R.; Auchus, R.J.; El-Hajj Fuleihan, G.; Handelsman, D.J.; Kalyani, R.R.; McClung, M.; Stuenkel, C.A.; Thorner, M.O.; Verbalis, J.G. Hormones and Aging: An Endocrine Society Scientific Statement. *J. Clin. Endocrinol. Metab.* **2023**, *108*, 1835–1874. [CrossRef]
99. Holmes, D.T.; Van Der Gugten, J.G.; Jung, B.; McCudden, C.R. Continuous Reference Intervals for Pediatric Testosterone, Sex Hormone Binding Globulin and Free Testosterone Using Quantile Regression. *J. Mass. Spectrom. Adv. Clin. Lab.* **2021**, *22*, 64–70. [CrossRef]
100. Pataky, M.W.; Dasari, S.; Michie, K.L.; Sevits, K.J.; Kumar, A.A.; Klaus, K.A.; Heppelmann, C.J.; Robinson, M.M.; Carter, R.E.; Lanza, I.R.; et al. Impact of Biological Sex and Sex Hormones on Molecular Signatures of Skeletal Muscle at Rest and in Response to Distinct Exercise Training Modes. *Cell Metab.* **2023**, *35*, 1996–2010.e6. [CrossRef]
101. Adult Complete Blood Count (CBC)—Mayo Clinic. Available online: https://www.mayoclinic.org/tests-procedures/complete-blood-count/about/pac-20384919 (accessed on 23 February 2025).
102. Pediatric Complete Pediatric Blood Cell Count (CBC) With Differential, Blood—Mayo Clinic Laboratories | Pediatric Catalog. Available online: https://pediatric.testcatalog.org/show/CBC (accessed on 23 February 2025).
103. Zierk, J.; Krebs, A.; Rauh, M.; Metzler, M.; Löscher, A.; Strasser, E.; Krause, S.W. Blood Counts in Adult and Elderly Individuals: Defining the Norms over Eight Decades of Life. *Br. J. Haematol.* **2020**, *189*, 777–789. [CrossRef]
104. Nah, E.-H.; Kim, S.; Cho, S.; Cho, H.-I. Complete Blood Count Reference Intervals and Patterns of Changes Across Pediatric, Adult, and Geriatric Ages in Korea. *Ann. Lab. Med.* **2018**, *38*, 503–511. [CrossRef] [PubMed]
105. Haugen, T.A.; Solberg, P.A.; Foster, C.; Morán-Navarro, R.; Breitschädel, F.; Hopkins, W.G. Peak Age and Performance Progression in World-Class Track-and-Field Athletes. *Int. J. Sports Physiol. Perform.* **2018**, *13*, 1122–1129. [CrossRef] [PubMed]
106. Allen, S.V.; Hopkins, W.G. Age of Peak Competitive Performance of Elite Athletes: A Systematic Review. *Sports Med.* **2015**, *45*, 1431–1441. [CrossRef]
107. Zavorsky, G.S.; Tomko, K.A.; Smoliga, J.M. Declines in Marathon Performance: Sex Differences in Elite and Recreational Athletes. *PLoS ONE* **2017**, *12*, e0172121. [CrossRef]
108. Lara, B.; Salinero, J.J.; Del Coso, J. The Relationship between Age and Running Time in Elite Marathoners Is U-Shaped. *AGE* **2014**, *36*, 1003–1008. [CrossRef]
109. Foster, C.; De Koning, J.J.; Thiel, C. Evolutionary Pattern of Improved 1-Mile Running Performance. *Int. J. Sports Physiol. Perform.* **2014**, *9*, 715–719. [CrossRef]
110. Sandbakk, Ø.; Solli, G.S.; Holmberg, H.-C. Sex Differences in World-Record Performance: The Influence of Sport Discipline and Competition Duration. *Int. J. Sports Physiol. Perform.* **2018**, *13*, 2–8. [CrossRef] [PubMed]
111. Earnest, C.P.; Rothschild, J.; Harnish, C.R.; Naderi, A. Metabolic Adaptations to Endurance Training and Nutrition Strategies Influencing Performance. *Res. Sports Med.* **2019**, *27*, 134–146. [CrossRef]
112. Santisteban, K.J.; Lovering, A.T.; Halliwill, J.R.; Minson, C.T. Sex Differences in VO2max and the Impact on Endurance-Exercise Performance. *Int. J. Environ. Res. Public Health* **2022**, *19*, 4946. [CrossRef]
113. Nikolaidis, P.T.; Zingg, M.A.; Knechtle, B. Performance Trends in Age-group Runners from 100 m to Marathon—The World Championships from 1975 to 2015. *Scand. J. Med. Sci. Sports* **2017**, *27*, 1588–1596. [CrossRef]
114. Lepers, R.; Knechtle, B.; Stapley, P.J. Trends in Triathlon Performance: Effects of Sex and Age. *Sports Med.* **2013**, *43*, 851–863. [CrossRef]
115. Nikolaidis, P.T.; Gangi, S.D.; Knechtle, B. World Records in Half-Marathon Running by Sex and Age. *J. Aging Phys. Act.* **2018**, *26*, 629–636. [CrossRef] [PubMed]
116. Rittweger, J.; di Prampero, P.E.; Maffulli, N.; Narici, M.V. Sprint and Endurance Power and Ageing: An Analysis of Master Athletic World Records. *Proc. R. Soc. B Biol. Sci.* **2009**, *276*, 683–689. [CrossRef] [PubMed]
117. Harnish, C.R.; Ferguson, H.A.; Swinand, G.P. Racing Demands of Off-Road Triathlon: A Case Study of a National Champion Masters Triathlete. *Sports* **2021**, *9*, 136. [CrossRef] [PubMed]
118. Harnish, C.R.; Swinand, G.P.; Fisher, A.E. Making History in 1-Hour: How Sex, Aging, Technology, and Elevation Effect the Cycling Hour Record. *Med. Sci. Sports Exerc.* **2023**. [CrossRef]
119. Ganse, B.; Kleerekoper, A.; Knobe, M.; Hildebrand, F.; Degens, H. Longitudinal Trends in Master Track and Field Performance throughout the Aging Process: 83,209 Results from Sweden in 16 Athletics Disciplines. *GeroScience* **2020**, *42*, 1609–1620. [CrossRef]
120. Bagley, L.; McPhee, J.S.; Ganse, B.; Müller, K.; Korhonen, M.T.; Rittweger, J.; Degens, H. Similar Relative Decline in Aerobic and Anaerobic Power with Age in Endurance and Power Master Athletes of Both Sexes. *Scand. J. Med. Sci. Sports* **2019**, *29*, 791–799. [CrossRef]
121. Bernard, T.; Sultana, F.; Lepers, R.; Hausswirth, C.; Brisswalter, J. Age-Related Decline in Olympic Triathlon Performance: Effect of Locomotion Mode. *Exp. Aging Res.* **2009**, *36*, 64–78. [CrossRef]

122. Wright, V.J.; Perricelli, B.C. Age-Related Rates of Decline in Performance among Elite Senior Athletes. *Am. J. Sports Med.* **2008**, *36*, 443–450. [CrossRef]
123. Reaburn, P.; Dascombe, B. Endurance Performance in Masters Athletes. *Eur. Rev. Aging Phys. Act.* **2008**, *5*, 31–42. [CrossRef]
124. Gava, P.; Giuriati, W.; Ravara, B. Gender Difference of Aging Performance Decay Rate in Normalized Masters World Records of Athletics: Much Less than Expected. *Eur. J. Transl. Myol.* **2020**, *30*, 8869. [CrossRef] [PubMed]
125. Ganse, B.; Drey, M.; Hildebrand, F.; Knobe, M.; Degens, H. Performance Declines Are Accelerated in the Oldest-Old Track and Field Athletes 80 to 94 Years of Age. *Rejuvenation Res.* **2021**, *24*, 20–27. [CrossRef] [PubMed]
126. Lazarus, N.R.; Harridge, S.D. Declining Performance of Master Athletes: Silhouettes of the Trajectory of Healthy Human Ageing? *J. Physiol.* **2017**, *595*, 2941–2948. [CrossRef] [PubMed]
127. Tanaka, H.; Seals, D.R. Endurance Exercise Performance in Masters Athletes: Age-Associated Changes and Underlying Physiological Mechanisms: Endurance Performance and Masters Athletes. *J. Physiol.* **2008**, *586*, 55–63. [CrossRef]
128. Lepers, R.; Cattagni, T. Age-Related Decline in Endurance Running Performance–An Example of a Multiple World Records Holder. *Appl. Physiol. Nutr. Metab.* **2018**, *43*, 98–100. [CrossRef] [PubMed]
129. Young, B.W.; Weir, P.L.; Starkes, J.L.; Medic, N. Does Lifelong Training Temper Age-Related Decline in Sport Performance? Interpreting Differences Between Cross-Sectional and Longitudinal Data. *Exp. Aging Res.* **2007**, *34*, 27–48. [CrossRef]
130. Ganse, B.; Degens, H. Current Insights in the Age-Related Decline in Sports Performance of the Older Athlete. *Int. J. Sports Med.* **2021**, *42*, 879–888. [CrossRef] [PubMed]
131. Korhonen, M.T.; Mero, A.A.; Alen, M.; Sipilä, S.; Häkkinen, K.; Liikavainio, T.; Viitasalo, J.T.; Haverinen, M.T.; Suominen, H. Biomechanical and Skeletal Muscle Determinants of Maximum Running Speed with Aging. *Med. Sci. Sports Exerc.* **2009**, *41*, 844–856. [CrossRef]
132. Korhonen, M.T.; Suominen, H.; Mero, A. Age and Sex Differences in Blood Lactate Response to Sprint Running in Elite Master Athletes. *Can. J. Appl. Physiol.* **2005**, *30*, 647–665. [CrossRef]
133. Reaburn, P.; Dascombe, B. Anaerobic Performance in Masters Athletes. *Eur. Rev. Aging Phys. Act.* **2009**, *6*, 39. [CrossRef]
134. Dahl, J.; Degens, H.; Hildebrand, F.; Ganse, B. Age-Related Changes of Sprint Kinematics. *Front. Physiol.* **2019**, *10*, 613. [CrossRef] [PubMed]
135. Young, B.W.; Medic, N.; Weir, P.L.; Starkes, J.L. Explaining Performance in Elite Middle-Aged Runners: Contributions from Age and from Ongoing and Past Training Factors. *J. Sport. Exerc. Psychol.* **2008**, *30*, 737–754. [CrossRef]
136. Easthope, C.S.; Hausswirth, C.; Louis, J.; Lepers, R.; Vercruyssen, F.; Brisswalter, J. Effects of a Trail Running Competition on Muscular Performance and Efficiency in Well-Trained Young and Master Athletes. *Eur. J. Appl. Physiol.* **2010**, *110*, 1107–1116. [CrossRef]
137. Suominen, H. Ageing and Maximal Physical Performance. *Eur. Rev. Aging Phys. Act.* **2011**, *8*, 37–42. [CrossRef]
138. Sayer, A. A Complete List of Running World Records (Updated 2024). 2024. Available online: https://marathonhandbook.com/running-world-records/ (accessed on 25 January 2025).
139. Stats | World Athletics | World Athletics. Available online: https://worldathletics.org/stats-zone (accessed on 23 February 2025).
140. Rodrigues, A.M.M.; E Silva, M.J.C.; Mota, J.; Cumming, S.P.; Sherar, L.B.; Neville, H.; Malina, R.M. Confounding Effect of Biologic Maturation on Sex Differences in Physical Activity and Sedentary Behavior in Adolescents. *Pediatr. Exerc. Sci.* **2010**, *22*, 442–453. [CrossRef] [PubMed]
141. Miller, S.M.; Siegel, J.T. Youth Sports and Physical Activity: The Relationship between Perceptions of Childhood Sport Experience and Adult Exercise Behavior. *Psychol. Sport. Exerc.* **2017**, *33*, 85–92. [CrossRef]
142. Bell, D.R.; DiStefano, L.; Pandya, N.K.; McGuine, T.A. The Public Health Consequences of Sport Specialization. *J. Athl. Train.* **2019**, *54*, 1013–1020. [CrossRef] [PubMed]
143. Bolger, L.E.; Bolger, L.A.; O' Neill, C.; Coughlan, E.; O'Brien, W.; Lacey, S.; Burns, C. Age and Sex Differences in Fundamental Movement Skills Among a Cohort of Irish School Children. *J. Mot. Learn. Dev.* **2018**, *6*, 81–100. [CrossRef]
144. Hardy, L.L.; Barnett, L.; Espinel, P.; Okely, A.D. Thirteen-Year Trends in Child and Adolescent Fundamental Movement Skills: 1997–2010. *Med. Sci. Sports Exerc.* **2013**, *45*, 1965–1970. [CrossRef]
145. Behan, S.; Belton, S.; Peers, C.; O'Connor, N.E.; Issartel, J. Moving Well-Being Well: Investigating the Maturation of Fundamental Movement Skill Proficiency across Sex in Irish Children Aged Five to Twelve. *J. Sports Sci.* **2019**, *37*, 2604–2612. [CrossRef]
146. Eyre, E.L.J.; Walker, L.J.; Duncan, M.J. Fundamental Movement Skills of Children Living in England: The Role of Ethnicity and Native English Language. *Percept. Mot. Ski.* **2018**, *125*, 5–20. [CrossRef] [PubMed]
147. Adeyemi-Walker, L.J.; Duncan, M.; Tallis, J.; Eyre, E. Fundamental Motor Skills of Children in Deprived Areas of England: A Focus on Age, Gender and Ethnicity. *Children* **2018**, *5*, 110. [CrossRef]
148. Bardid, F.; Huyben, F.; Lenoir, M.; Seghers, J.; De Martelaer, K.; Goodway, J.D.; Deconinck, F.J.A. Assessing Fundamental Motor Skills in Belgian Children Aged 3–8 Years Highlights Differences to US Reference Sample. *Acta Paediatr.* **2016**, *105*, 13380. [CrossRef] [PubMed]

149. Armstrong, N.; Welsman, J.R. Development of Aerobic Fitness during Childhood and Adolescence. *Pediatr. Exerc. Sci.* **2000**, *12*, 128–149. [CrossRef]
150. Armstrong, N.; Welsman, J.O. Traditional and New Perspectives on Youth Cardiorespiratory Fitness. *Med. Sci. Sports Exerc.* **2020**, *52*, 2563–2573. [CrossRef]
151. Armstrong, N.; Welsman, J.R.; Kirby, B.J. Performance on the Wingate Anaerobic Test and Maturation. *Pediatr. Exerc. Sci.* **1997**, *9*, 253–261. [CrossRef]
152. Tolfrey, K.; Campbell, I.G.; Batterham, A.M. Aerobic Trainability of Prepubertal Boys and Girls. *Pediatr. Exerc. Sci.* **1998**, *10*, 248–263. [CrossRef]
153. Armstrong, N.; Welsman, J. The Development of Aerobic and Anaerobic Fitness with Reference to Youth Athletes. *J. Sci. Sport Exerc.* **2020**, *2*, 275–286. [CrossRef]
154. Petray, C.K.; Krahenbuhl, G.S. Running Training, Instruction on Running Technique, and Running Economy in 10-Year-Old Males. *Res. Q. Exerc. Sport.* **1985**, *56*, 251–255. [CrossRef]
155. Welsman, J.; Armstrong, N. Interpreting Aerobic Fitness in Youth: The Fallacy of Ratio Scaling. *Pediatr. Exerc. Sci.* **2019**, *31*, 184–190. [CrossRef]
156. Emig, T.; Adam, G. Evolution of World Running Record Performances for Men and Women: Physiological Characteristics. *Front. Physiol.* **2024**, *15*, 1372092. [CrossRef]
157. Gorzi, A.; Khantan, M.; Khademnoe, O.; Eston, R. Prediction of Elite Athletes' Performance by Analysis of Peak-performance Age and Age-related Performance Progression. *Eur. J. Sport. Sci.* **2022**, *22*, 146–159. [CrossRef] [PubMed]
158. Foss, J.L.; Sinex, J.A.; Chapman, R.F. Career Performance Progressions of Junior and Senior Elite Track and Field Athletes. *J. Sci. Sport. Exerc.* **2019**, *1*, 168–175. [CrossRef]
159. Agudo-Ortega, A.; Del Cerro, J.S.; Salinero, J.J.; González-Rave, J.M. Unveiling the Development of Sprint Athletes: Percentile Patterns, Peak Performance Age, and a Performance Progression Model. *J. Hum. Kinet.* **2024**, *94*, 147. [CrossRef] [PubMed]
160. Wiebe, C.G.; Gledhill, N.; Warburton, D.E.; Jamnik, V.K.; Ferguson, S. Exercise Cardiac Function in Endurance-Trained Males versus Females. *Clin. J. Sport. Med.* **1998**, *8*, 272–279. [CrossRef] [PubMed]
161. Waldron, S.; DeFreese, J.D.; Register-Mihalik, J.; Pietrosimone, B.; Barczak, N. The Costs and Benefits of Early Sport Specialization: A Critical Review of Literature. *Quest* **2020**, *72*, 1–18. [CrossRef]
162. Harridge, S.D.; Lazarus, N.R. Physical Activity, Aging, and Physiological Function. *Physiology* **2017**, *32*, 152–161.
163. Ferguson, H.A.; Harnish, C.; Chase, J.G. Using Field Based Data to Model Sprint Track Cycling Performance. *Sports Med. Open* **2021**, *7*, 20. [CrossRef]
164. Ferguson, H.; Harnish, C.; Klich, S.; Michalik, K.; Dunst, A.K.; Zhou, T.; Chase, J.G. Power-Duration Relationship Comparison in Competition Sprint Cyclists from 1-s to 20-Min. Sprint Performance Is More than Just Peak Power. *PLoS ONE* **2023**, *18*, e0280658. [CrossRef]
165. Armstrong, N.; Barker, A.R. New Insights in Paediatric Exercise Metabolism. *J. Sport. Health Sci.* **2012**, *1*, 18–26. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.