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Article

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Youth Running Performance Foreshadows Senior Outcomes in Males and Females

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Abstract

Analyses of running performance from youth to senior level typically focus on elite cohorts, resulting in restrictive age-related norms that limit talent evaluation. We longitudinally examine performances across distances from 100 m to 3,000 m, ranging from regional to international levels. For each distance and sex, performance corridors from ages 16 to 25 are approximated as curvilinear envelopes defined by non-linear boundaries of low and high performance gain. When race times at ages 16–19 are known, these corridors allow a performance level at age 25 to be estimated with an accuracy of about 3% (e.g., 1:54–1:58 in the female 800 m event). The coefficient of special endurance (KsA) refines this prediction by evaluating performances in neighboring distances, which constrains main-distance development. In conclusion, running performance across 100–3,000 m between ages 16 and 19 foreshadows senior outcomes within a 3% margin, further refined by KsA values. To support athletic practice, we introduce open-source web applications that map youth race times of both male and female runners to performance corridors, delivering reliable age-specific time ranges. Our approach provides a framework for both talent identification and development, which is broadly applicable to centimeter-gram-second (CGS) sports.

Key words: longitudinal running data, performance corridors, track running, coefficient of special endurance, KsA value, talent identification and development

Introduction

Analyzing performance progression from youth to senior level is a vital area of sport science, particularly in cgs sports such as athletics or weightlifting where performance is measured in centimeters, grams, or seconds. This research aims to identify typical age-related performance trajectories, set realistic performance goals of athletes, determine the age of peak performance for different disciplines, and drive age-related long-term training programs. Ultimately, these insights provide a basis for both talent identification and talent development, which are important for coaches, professional sports clubs, and sports federations [1–4].

Peak-performance age has been systematically analyzed in top international track-and-field athletes for sprint and explosive events, middle distances, and endurance events. While peak performance typically occurs between the ages of 25 and 27 in sprints, hurdles, jumps, throws, and middle-distance events, marathon and ultra-marathon runners peak later, between 30 and 40 years, with no significant differences observed between sexes [5]. Performances of more than 2,000 athletes from track-and-field disciplines finishing in the top 12–16 of Olympic Games or World Athletics Championships were modeled to estimate the window of peak performance. It was found for both sexes that the peak-performance age is between 23 and 27 years for sprints, jumps, and 800 m to 10,000 m events, and 27 to 28 years for throws [6]. Several other studies in athletics show similar peak ages for world-class athletes [1,2,5,7–9], implying a development period for potential world-class athletes of at least 10 years (from 16 to 25 years) from the youth to the senior level - a timeframe that corresponds to the '10-year rule of attainment' [10].

Another question regarding performance progression in athletics is whether elite youth performances successfully predict senior-level success. A large-scale study of 67,600 top international athletes across all track-and-field disciplines and both sexes examined whether athletes in the U18 and U20 top-100 rankings maintained their status at the senior level [11]. Only 23.5% of U18 and 35.4% of U20 athletes transitioned into successful senior competitors, with female athletes showing slightly higher transition rates. A similar analysis focusing on world-class middle- and long-distance runners revealed youth-to-senior transition rates of 19% for males and 21% for females [12]. Out of 368 World Junior Championship finalists in middle- and long-distance events, 20.4% reach the IAAF Top Ten ranking within about 2.4 years [13]. All these career pathway data reflect the high drop-out rates of youth athletes observed by many national athletics federations, which stem from a complex interplay of social, psychological, and physiological factors [14,15].

Although peak-performance age and career progression pathways offer valuable insights for talent identification and training design, individual performance improvements from adolescence to adulthood vary significantly. This high variability complicates the establishment of reliable age-related norms for potential world-class athletes. An analysis of 775 elite track-and-field athletes demonstrated the existence of at least two distinct sub-groups: athletes who achieve peak performance early, potentially driven by greater innate talent, and those who excel later, likely reflecting superior training adaptability [16,17]. Similarly, a detailed look at the performance trajectories of international track-and-field athletes reveals that the magnitude of performance progression from the youth to the senior level varies greatly [1,4,7–9,18]. However, these studies have not closely addressed this variance in performance progression within otherwise homogeneous elite athletes.

Here, we hypothesized that accounting for the variance in the performance gain from the youth to the senior level allows for the establishment of performance corridors. These corridors are expected to narrow with advancing age, culminate in specific senior target performances, and define age-related performance ranges for a given target time. To this end, we focused on track-and-field sprint and middle-distance events (100 m to 3,000 m) in both sexes, analyzing the race-time gain of runner groups at regional, national, and international levels from ages 16 to 25. Furthermore, our objective was to establish theoretical trajectories of performance progression that are readily applicable to both sexes and across distances from 100 m to 3,000 m. Finally, we aimed to analyze whether the pace ratio - quantified using KsA values previously published by our group [19–21] - between performances in adjacent race events (e.g., 200 m/400 m) changes between ages 16 and 25. Overall, we aimed to establish age-related performance corridors for distances from 100 m to 3,000 m for both sexes that account for inter-individual variation in performance gains from youth to senior level, providing a foundation for identifying sprint and middle-distance talents.

Results

Multi-dataset approach to elucidate performance progression of runners from youth to senior level across distances from 100 m to 3,000 m in both sexes

To establish a robust longitudinal dataset, we used annual ranking lists from GBR (**Tab. 1**) because the respective Power-of-10 database contains performance records down to the regional level. From an initial pool of more than 120,000 performance records (covering both sexes, ten years, and six distances, with approximately 1,000 runners per distance and year), we typically identified 50–120 runners per distance who had recorded at least five performances between ages 16 and 25. This enables separate analysis for national- and regional-level runners (e.g., 51.97 vs. 57.05 s for female 400-m runners). To validate the GBR findings, we additionally performed longitudinal analyses of male and female runners from GER using previously published [19–21] datasets (**Tab. 1**).

To compare the performance progression of national-class runners from GBR and GER with world-class athletes, we examined the World Athletics all-time top-10 lists from 100 to 3,000 m (**Tab. 1).** For the national-class runners, we additionally identified athletes who recorded performances in two adjacent events (e.g., 100 m and 200 m) at the same age. These data were used to calculate KsA values for each sex and distance pair from ages 16 to 25 (**Tab. S09** and **10** for males**, Table S12** and **S13** for females). To validate longitudinal KsA values, we obtained cross-sectional KsA values from annual national top 30 lists from GER, stratified by sex and the age groups U18, U20, U23, and senior (**Tab. S11** for males and **Tab. S14** for females). This re-analysis was restricted to the period 1980–2009 and has been described previously [19]. Collectively, our multi-dataset approach helps to elucidate the performance progression of runners across different performance tiers, covering distances from 100 m to 3,000 m and ages 16 to 25 in both male and female athletes.

Performance levels of male runners classified as regional, national, or international class remained distinct from ages 16 to 25 across events ranging from 100 to 3000 m

To investigate whether performance progression from ages 16 to 25 differed between performance tiers, we first compared national- and regional-class male runners from GBR across events ranging from 100 to 3000 m. Although senior-level performances differed by only ~3.7–4.6% in the 100, 200, 800, and 1500 m, with a slightly greater difference in the 400 m (5.4%) and a smaller difference in the 3000 m (1.8%), performance levels remained largely

distinct from ages 16 to 25 (**Fig. 1A–F**). For example, 200-m runners with personal bests achieved by age 25 averaging 20.86 s were faster across all ages from 16 to 25 than runners averaging 21.65 s (**Fig. 1B).** A comparable separation was evident among 1,500-m runners (3:38.5 vs. 3:47.7 min; **Fig. 1E**). Thus, the performance gap between national- and regional-class male runners observed at the senior level was already apparent in the U18 and U20 age categories.

For external validation of the longitudinal GBR findings, we analyzed performance progression in male runners from GER. Across all evaluated distances, the German national-class runners achieved personal bests by age 25 that closely mirrored those of their GBR counterparts (e.g., 7:54.7 vs. 7:52.4 min over 3,000 m for GER and GBR, respectively). GBR and GER male runners demonstrated nearly identical performance progression from age 16 to 25 across the 100 to 3,000 m events (**Fig. 1A–F**). We conclude that male performance progression at the national level across 100 to 3,000 m from youth to senior level follows a generalizable pattern.

Next, we examine whether performance progression across 100 to 3,000 m differentiates world-class from national-class runners as early as youth. The performance difference between world-class and national-class runners (GBR, GER) ranges from 4.9% to 6.5% across events (e.g., 3:27.8 vs. 3:38.5 min over 3,000 m for world-class and GBR runners, respectively). Similar to the regional- versus national-class comparison, the performance progression of world-class and national runners remain distinctly separated throughout the 16-to-25-year age span (**Fig. 1A-F**). Overall, performance differences of approximately 5% at the senior level from 100 m to 3,000 m can already be observed between the ages of 16 and 19 in male runners.

Similar to male runners, performance levels of <u>female</u> runners classified as regional, national, or international class remained distinct from ages 16 to 25 across events ranging from 100 to 3000 m

To examine whether the performance progression from ages 16 to 25 differed across performance levels in female runners, we applied the same approach used for males (**Fig. 2A–F**). At the senior level, performance differences ranged from 6.8% to 8.8% between regional- and national-class runners (e.g., 2:12.0 vs. 2:03.4 min over 800 m; **Fig. 2D**) and from 4.0% to 10.0% between national- and world-class runners (e.g., 51.97 vs. 49.03 s over 400 m; **Fig. 2C**). Despite relatively high within-group variability, performance progression across these three performance levels remained largely distinct from ages 16 to 25. Thus, as in male runners,

senior-level performance differences between regional-, national-, and international-class female runners were already evident during youth.

Weighted per-year time reduction model captures performance trajectories from ages 16 to 25 across 100–3,000 m events in regional-, national-, and international-class runners of both males and females

A closer inspection of performance progression from ages 16 to 25 across events from 100 to 3000 m and in both sexes (**Figs. 1, 2**) revealed smooth trajectories that were neither linear nor strongly exponential. To describe such trajectories, Peter Coe (father and coach of Sebastian Coe) and David E. Martin developed a simple *weighted per-year time reduction* model, assuming progressively smaller year-to-year performance gains [19]. For example, over a 10-year progression period (e.g., ages 16–25), this model assigns 53.33% of the total improvement to the first four years (up to age 19; U20). The resulting theoretical trajectories closely matched the observed progression across all evaluated distances and in both sexes. For example, national- and world-class male 1500 m runners with mean personal bests by age 25 of 3:38.5 and 3:27.8 min, respectively, showed trajectories that did not differ significantly (e. g., 3:27.8 min group: equivalence test, adjusted for multiple comparisons, $p < 0.001$ for ages 16, 18-25, but not for age 17) from the theoretical trajectories (**Fig. 3A**). As another example, a similar agreement was observed in regional- and national-class female 800 m runners (2:12.03 vs. 2:03.4 min; **Fig. 3B**). Thus, the *weighted per-year time reduction* model adequately describes year-to-year performance improvements from ages 16 to 25 across 100–3,000 m events in regional-, national-, and international-class runners of both sexes.

Performance improvements between ages 16 and 25 in male runners across 100–3000 m events reach 5–10% at the median and 10–15% at the 90th percentile

We aimed to quantify the performance gains between ages 16 to 25 in male runners across events from 100 to 3,000 m. As performance level was only weakly associated with performance gains across all evaluated distances ($R^2 < 0.1$), data from regional-, national-, and international-class runners were pooled for each event. Individual gains (expressed in seconds) were plotted for each distance and sex, and the respective 25th, 50th (median), 75th, and 90th percentiles were calculated (**Fig. 3C-E**). For example, median improvements in male runners between ages 16 and 25 were 0.56 s (100 m), 1.17 s (200 m), 3.07 s (400 m), 7.09 s (800 m), 21.35 s (1,500 m), and 52.91 s (3,000 m). These gains corresponded to relative improvements of approximately 5–7% across the 100–800 m events and approximately 10% in the 1500 and

3000 m events. At the 90th percentile, gains from ages 16 to 25 reached 0.85 s (100 m), 1.99 s (200 m), 4.38 s (400 m), 12.54 s (800 m), 30.97 s (1,500 m), and 81.22 s (3,000 m), corresponding to relative gains of approximately 10–15%. Overall, relative performance gain increased with event distance in male runners.

Performance improvements between ages 16 and 25 in female runners across 100–3000 m events reach 5–10% at the median and 10–17% at the 90th percentile

To quantify female performance gains, we applied the same approach used for males (**Fig. 3C, D**). Overall, gains between ages 16 to 25 are very similar between male and female runners across distances from 100 to 3,000 m. The median gains of female runners between ages 16 and 25 were 0.62 s (100 m), 1.31 s (200 m), 3.05 s (400 m), 8.39 s (800 m), 23.21 s (1,500 m), and 56.60 s (3,000 m), corresponding to approximately 5–7% gains across the 100–800 m events and approximately 10% gains in the 1,500 m and 3,000 m events. At the 90th percentile, improvements reached 1.06 s (100 m), 2.31 s (200 m), 5.66 s (400 m), 14.76 s (800 m), 35.11 s (1,500 m), and 90.93 s (3,000 m), corresponding to relative improvements of approximately 10–17%. As observed in males, relative performance gains increased with event distance in female runners.

Estimation of potential senior-level performance of individual male and female runners based on their performances at younger ages across events from 100 to 3000 m

To project senior-level performances of individual male and female runners based on youth performances, we developed performance corridors for different target times across distances from 100 to 3,000 m. For example, the 1,500 m corridors for male runners were centered on target times of 3:28, 3:34, and 3:40 min from age 25 onwards (up to age 35) **(Fig. 4A).** The 800 m corridors for female runners were, for example, centered on 1:54, 1:58, and 2:02 min. (**Fig. 4B**). The corridors were derived from the theoretical performance trajectories according to Coe/Martin [22] and the 25th and 90th percentiles of performance gains (**Fig. 3E**). The upper boundaries of the corridors represent the 90th percentile and thus greater gains, whereas the lower boundaries represent the 25th percentile and thus smaller gains.

The performance corridors with the respective target-times were designed to overlap until approximately ages 19 and to separate thereafter (**Fig. 4A, B**; see the three shaded areas). Consequently, performances of individual runners up to approximately ages 19 fall within two target-time corridors, whereas from about age 20 onward, a more precise estimate of future

performance becomes possible (see examples in **Fig. 4A, B**). In conclusion, we developed performance corridors with centered target times to estimate the senior-level performance potential of male and female runners across events from 100 to 3,000 m based on their performances at ages of about 16-19. The performance corridors are available as open-source web applications for male (https://leistungs-korridore-manner.replit.app) and female (https://leistungskorridore-frauen.replit.app) runners, respectively.

The pace ratio between performances in adjacent race events (e.g., 400 m/800 m) changes only slightly between ages 16 and 25 across distances from 100 m to 3,000 m in male runners

Because performance in a main running distance (e.g., 800 m) is influenced by performances at the lower and upper neighboring distances (e.g., 400 m, 1500 m), we aimed to investigate the progression of performance over two adjacent distances relative to each other between 16 and 25 years of age. To quantify this, we utilized the coefficient of special endurance (KsA), which is defined as the ratio of the pace (s/ 100 m) at the shorter distance to that at the longer distance [19–21]. We used male runners from GBR and GER who recorded performances over to adjacent distances throughout the entire age span. We additionally used average performances of German male runners across the U18, U20, U23, and senior men's age categories.

The KsA values of male runners from both GBR and GER for the distance pairs 100 m/200 m, 200 m/400 m, 400 m/800 m, and 1500 m/3000 m showed no obvious trends from ages 16 to 25, a pattern mirrored in the age-category dataset (**Fig. 5A-C).** For instance, the KsA value for the 100 m/200 m pair among GER runners increased non-significantly from 0.983004 at age 16 to 0.992897 at age 25. Theoretically, this shift corresponds to a KsA-mediated improvement in 200 m performance of 0.2 seconds assuming a constant 100 m time over the age span. By comparison, actual 200 m performance improved by 0.81 to 1.99 seconds (**Fig. 3E,** 25th and 90th percentiles). Consequently, this theoretically accounts for approximately 10–25% of overall performance gains over 200 m from ages 16 to 25, a proportion that similarly applies to the 400 m, 800 m, and 3000 m distances.

For the 800 m/1500 m pairs, the respective KsA values exhibit a continuous upward trajectory across all three datasets (GBR, GER, and age groups) between the ages of 16 and 25 (**Fig. 5D–E**). Among GER runners, for example, the 800 m/1500 m KsA values rises from 0.893738 at age 16 to 0.920749 at age 25. Assuming a constant 800 m time over the age span, this KsA-

mediated shift equates to a 7.2-second performance gain in the 1500 m event. Because the actual improvement of male runners ranges from 14.78 to 30.97 seconds (**Fig. 3E**, 25th and 90th percentiles), the KsA-driven component accounts for roughly 23–50% of the total performance gain in the 1,500 m run from ages 16 to 25. Overall, the KsA values - describing the relative pace ratio between performances in two adjacent distances - across distance pairs from 100 m/200 m to 1500 m/3000 m change slightly in male runners from age 16 to 25.

Similar to male runners, the pace ratio between performances in adjacent race events (e.g., 400 m/800 m) changes only slightly between ages 16 and 25 across distances from 100 m to 3,000 m in female runners

To examine the progression of performance over two adjacent distances relative to each other between ages 16 and 25 in female runners, we applied the same approach used for males. The analysis revealed a continuous upward trend in KsA values across all distance pairs (from 100 m/200 m up to 1500 m/3000 m) and datasets (GBR, GER, and age groups) between ages 16 and 25 (**Fig. 6A–E**). To illustrate, GBR female runners experienced an increase in their 100 m/200 m KsA from 0.906563 to 0.928596 over this decade. Assuming a constant 100 m time, this KsA shift translates to a minor 0.15-second improvement in the 200 m event. Given that actual 200 m performance improved from ages 16 to 25 by 1.07 to 2.31 seconds (**Fig. 3E**, 25th and 90th percentiles), the KsA component accounts for approximately 6.5–14% of the overall progression. Similarly, the 800 m/1500 m KsA for GBR females rose from 0.899236 to 0.920210 between ages 16 and 25, accounting for a theoretical 5.9-second gain in the 1500 m. With actual improvements of 15.63 to 35.11 seconds (**Fig. 3E**, 25th and 90th percentiles), the increase in the KsA value drives roughly 17–38% of the total performance enhancement in the 1,500 m event. A comparable proportion holds true for the 400, 800, and 3000 m event. Thus, the influence of the increase in the KsA values on performance progression from ages 16 to 25 across distances from 100 to 3000 m is rather limited in female runners.

Discussion

Our study provides several novel methodological and conceptual aspects for evaluating the performance of youth runners with respect to their performance potential at the senior level. Specifically, our study 1) focuses on distances and an age range that enable a systematic analysis of sprint and middle-distance performances in both sexes; 2) provides large longitudinal datasets (six distances from 100 to 3000 m, both sexes, different performance levels) to follow performance progression from the youth to the senior level; 3) shows that a weighted per-year time reduction approach [22] approximates performance improvements, regardless of distance, sex, and performance level; 4) defines the inter-individual range of youth-to-adult performance gains across distances from 100 to 3000 m of both sexes; 5) implies that the performance progression of both the lower and upper neighboring distance (e. g., 400 m, 1500 m) limits progression over the main distance (e. g., 800 m); 6) establishes performance corridors that enable a rough estimation of a youth runner's potential, which is further refined by the previously published KsA approach [19–21] exemplifies the capturing of unusual career trajectories (e. g., cross-over, early-blooming, or event-switching athletes) of runners by combining performance corridors with the KsA approach; 8) introduces a 7-step framework that allows for estimating a youth runner's potential with a reliability of about 3%; and 9) provides an open-source web application that allows race times of individual runners to be assigned to the corresponding performance corridors.

The selected distances and age range enable a longitudinal and systematic analysis of sprint and middle-distance performances, yielding consistent results in both sexes

To gain insight into performance progression from the youth to the senior level in both male and female runners, race times were analyzed across distances from 100 to 3,000 m, spanning a wide performance spectrum (e.g., 800-m times ranging from 1:42 to 1:52 min at the senior level). These events were selected because they were consistently represented across all age groups in both sexes and allow for the analysis of relationships between adjacent distances using the KsA approach. Analyses were restricted to ages 16–25 years, as substantial gaps in performance records before age 16 limited reliable longitudinal tracking. Only large cross-sectional data in athletics from Norway spanning ages 11 to 18 are available, providing an estimate regarding performance enhancement prior to age 16 [9].

The selected age range (ages 16 to 25) also encompasses the period in which personal best performances are typically achieved, with mean performance levels plateauing at about age 25 [2,6,9]. Beyond age 25, rankings increasingly become subject to survivor bias, predominantly retaining athletes capable of sustaining exceptionally high performance levels. Although peak athletic performances occasionally occur beyond the age of 25, this phenomenon is largely confined to elite endurance events—and even then, subsequent gains remain marginal [2,6,9]. However, because several runners—particularly in longer running events—reach their personal bests after the age of 25, we accounted for this by extending the performance corridors up to age 35, thereby keeping potential for further improvement open.

Longitudinal datasets across distances, sexes, and performance levels enable comprehensive insights into performance progression of runners from ages 16 to 25

Our longitudinal analysis - tracking individual runners across ages 16 to 25 - captures over 100 runners for most distances, with the majority retaining at least 6 to 7 out of 10 possible age-related records. The inherent difficulty of generating such datasets (**Tab. S01-S14**) is highlighted by our data from GBR (**Tab. S01/04/09/12**): from approximately 120,000 raw race times (10 years, 6 distances, ~ 1,000 times per year, distance, and sex), we yielded only about 7,000 profiles (~5.8%). This attrition stems primarily from high drop-out rates among youth runners, with many individuals appearing only 1 to 3 times in the rankings. Our datasets might represents the most systematically compiled longitudinal collections for distances ranging from 100 to 3,000 meters, whereas previous studies [1,7,9,23] focus on sprint disciplines or more widely spaced distances (100, 800, and 10,000 m)

Unlike previous research focused on international athletes [7–9,18], our datasets encompass a broad spectrum of performance levels. This broader scope reveals a high variance in performance gain within each performance tier, enabling the derivation of reliable performance corridors. A second commonality across the different performance levels concerns the age-related trajectories, which are remarkably similar (**Fig. 1/2**) and can be captured by Coe and Martin's weighted per-year time reduction approach [22]. Consistently of our data is further underscored by our national-class cohorts: race times from GBR were specifically collected for longitudinal tracking, whereas those from GER were initially compiled for the KsA approach [19]. Despite these methodological differences in primary collection, both cohorts yield virtually identical age-related trajectories across all distances (100 m to 3,000 m) and both sexes. Thus, the

presented datasets enables comprehensive insights into performance progression of runners from youth to senior-level**.**

The weighted per-year time reduction approach approximates age-related improvements of running performance, regardless of distance, sex, and performance level

Due to the high variance in performance gains from age 16 to 25 across distances from 100 to 3000 m, the question arises as to how these improvements are best mapped by trajectories. Both practical experience and the literature (e.g., showing a quadratic function of age-related 800 m performance [18],) consistently suggest a non-linear relationship between performance gains and age. Trajectories show greater progress during youth and smaller gains at the senior level [1,7,9]. We utilized the weighted per-year time reduction approach introduced by Coe and Martin [22], which approximates the observed performance gains across distances, sex, and performance levels (**Fig. 3A/B** as examples). The model implies that about 50% of the total performance gain is achieved between the ages of 16 and 19, illustrating that the age-related trajectories are neither linear nor strongly exponential. Experience shows that individual runners' progress often occurs in "jumps" followed by plateaus. Therefore, we did not use the trajectories directly, but instead defined performance corridors based on them to evaluate the runners' potential.

The established standard percentiles of age-related performance gains match reported findings compiled from diverse groups of runners

As found for distances from 100 to 3000 m of both sexes, the performance gains from ages 16 to 25 is just as variable within performance levels as it is across them. We therefore established standard percentiles of performance gains (**Tab. 3E)** based on the variance of all analyzed runners (**Tab. 3C/D**), independently of their performance level (e.g., 100 m sprinters from 9.76 to 10.79 s). For example, a 3.8-second improvement from ages 16 to 25 over 400 m in males maps to the 75th standard percentile, indicating that only 25% exceed it. Comparing our standard percentiles (**Tab. 2**) with findings from the literature [1,6,7,18], elite male and female 100m and 400m runners (e.g., mean performances of 9.97 s for males and 11.07 s for females) show improvements corresponding to the 50th–90th percentiles. When world-class sprinters of both sexes (e.g., mean performances of 10.00 s for males and 10.90 s for females) are differentiated by whether they were already ranked in the U18 category or appeared only in senior-level rankings, their progression falls into the 25th–50th percentiles. Elite 1500m runners of both sexes (e.g., mean performances of 3:32.40 min for males and 4:00.60 min for females) match the 25th percentile, whereas high-level national-class 800m and 1500m runners (e.g.,

mean performances of 3:38.38 min for males and 4:07.34 min for females) correspond to the 90th percentile. Overall, literature-reported average performance gains from youth to senior level across sexes and various distances (100 m–1,500 m) match our proposed 25th–90th standard percentiles, with no apparent relationship between performance level and percentile assignment

We suggest that the magnitude of performance gains appears to depend on the contextual factors that shaped the composition of the athlete cohort studied. This can also be assumed for the ongoing debate regarding whether certain achievements in youth are necessary or not for success in adulthood [11–13,15–17]. A wide variance in performance gains independent of performance level is also supported by practical experience: Some world-class athletes achieve exceptional performances early on, followed by relatively small performance gains, whereas others exhibit substantial performance progression. Similarly, among regional-class runners, some display strong early performances with limited subsequent gains, whereas others improve significantly and continuously over a long period. It has been suggested [17] that athletes who excel early may possess greater innate talent, whereas those who excel later may exhibit superior training adaptability. A family study suggested that even the trainability of VO2max as an important determinant of running performance is genetically co-determined [24]. Although our findings cannot resolve these interesting questions, the established standard percentiles establish a framework for expected performance gains between ages 16 and 25, regardless of the athlete's performance level.

The age-dependent changes in the KsA values for the distance pairs from 100/200 m to 1500/3000 m are small and contribute only marginally to performance gains

Due to the close relationship between performances in a main event (e. g., 200 m) and their lower and upper neighboring distances (e. g., 100 m, 400 m), we examined age-related KsA values, a measure for relative pace loss between adjacent distances [19–21]. This analysis was done for five distance pairs (100/200 m to 1500/3000 m) using both longitudinal data from national-class runners (GBR, GER) and cross-sectional data. The three datasets show a remarkable consistency regarding the age-dependent KsA values in both sexes (**Fig. 5, 6**). Since the KsA values for the 5 distance pairs remain relatively constant from ages 16 to 25, it can be assumed that any age-related performance gain in a main event (e.g., 200 m or 800 m) must be accompanied by a corresponding performance gains in the respective lower neighboring distance (e. g., 100 m or 400 m). Conversely, this implies that overly early specialization in a

main event - while neglecting the lower neighboring distance - rapidly leads to performance stagnation or only marginal gains. This hypothesis is supported by data on world-class sprinters, demonstrating that athletes competing in the 100–200 m and 200–400 m couples, respectively, achieve better peak performances than single-discipline specialists [25].

In our view, the strong influence of the lower neighboring distance on performance in the main event is a critical and frequently neglected aspect of athletic talent development. This should substantially shape youth training programs. Conversely, an exclusive focus on improving the lower neighboring distance can lead to the neglect of the upper neighboring distance, which also makes a substantial contribution to developing the progress in the main event. However, optimizing the KsA values (lower neighboring distance/main distance and main distance/upper neighboring distance) during the peak performance age span (approximately 23–27 years) represents an important performance reserve for fully exploiting a runner's potential. Overall, performance gains from the youth to the senior level depend only marginally on the improvement of KsA values; this applies across all distances ranging from 100 to 3,000 m for both sexes.

Evaluating a runner's potential based on performance progression can be refined by using the KsA-approach

As a first step to evaluate an individual runner's potential, we propose utilizing our established performance corridors. Because performance differences between adjacent corridors amount to approximately 3% (e.g., 1:54 vs. 1:58 min for a female 800m runner), even a rough estimate of potential senior-level times based on youth performances becomes feasible. For instance, Runner A (age 22) is an extraordinary world-class female 800m runner who reaches or even exceeds the 800m performance corridor targeting 1:54.0 min (**Tab. 3**), whereas Runner B (age 20) - an exceptional national-level female 800m runner - also reaches this 1:54.0 min corridor.

As a second step to refine the evaluation, we propose applying our KsA-approach. It utilizes normative values for the pace loss between two adjacent distances (e.g., KsA 400m/800m). To extend our example, based on the 1:54.0 and 1:58.0 performance corridors and assuming that female runners A and B achieve KsA 400m/800m value of 0.893546 corresponding to the 75th KsA percentile [20], we derived age-related target times for the 400m distance (**Tab. 3**). While Runner A consistently achieves or even surpasses the calculated 400m benchmarks for the 1:54 corridor across all ages, Runner B 400 m records fall partly between the 400 m thresholds

deduced from the 1:54 and 1:58 corridors. Consequently, whereas both the 400m and 800m performances of Runner A align clearly with the 1:54 corridor, only Runner B's 800m time supports this tier, with her 400 m records pointing toward a time between 1:54 and 1:58 min. It is therefore realistic to project a target time of about 1:56 min. for Runner B, unless she can markedly improve her 400m performance from 53.8s to approximately 50.9s over the coming years (from age 20 to 25). We emphasize that an ideal potential analysis should also include performances over the upper neighboring distance (e. g., KsA 800/1500 m values); unfortunately, this is often not possible for the female 800 m runners examined here, as they rarely or do not compete over 1,500 m. Overall, we recommend using these performance corridors as an initial step to evaluate an athlete's potential, which can then be refined using the two KsA values for a given main race distance.

Evaluating late entrants, cross-over, career-extending, and early-blooming athletes is challenging – exemplified by such unusual athletes

Our evaluation scheme is primarily designed for runners with structured, age-appropriate, and well-rounded athletics training backgrounds starting around age 16. However, late-entrant and/or cross-over athletes (e.g., from soccer or team handball) frequently achieve exceptional (initial) performances. For such athletes, performance progression is likely to be more limited, tending to fall within the lower boundary of the respective performance corridor (25th–50th percentile of performance increase; **Fig. 3E**). We assume this because such athletes frequently come from sports whose training resembles the demands of the respective athletic discipline (e.g., soccer and 800 m training).

For example, a former soccer player with one year of 800 m training might already run 49.8 s over 400 m and 1:51 min over 800 m at age 21. Assuming that this cross-over athlete improves within the 25th–50th percentile range for both 400 m and 800 m (1.9–3.1 s and 5.3–7.1 s, respectively), projected times of 46.7–47.9 s and 1:43.9–1:45.7 min would result. This rough estimate can be cross-check by combining 400 m projections with the 75th KsA 400/800 m percentile [21], resulting in an 800 m potential of 1:44.0 to 1:46.8 min. These estimates should be useful for training design; however, athletes and coaches must keep in mind that late entrants and/or cross-over athletes often exhibit lower training tolerance and higher injury susceptibility than seasoned 800 m runners.

Another athlete type prolongs their career for an unusually long time (up to age ~35) and achieves personal bests between ages 30 and 35. An impressive example is Shelly-Ann Fraser-Pryce, who ran the 100 m at age 17 in 11.57 s, at age 23 in 10.73 s, and achieved her personal best at age 35 in 10.60 s. Her 1.17 s increase from 17 to 35 falls within our proposed 90th–95th percentile (**Fig. 3E),** implying she reached her maximum. Another prominent example is 800 m runner Mark English, who progressed from 1:52.25 min at age 16 to 1:44.84 min at age 20, and 1:42.78 min at age 33. His 9.48 s increase falls within the 75th percentile. Middle-distance runner Georgia Hunter Bell achieved 2:09.16 min at age 16 and 2:03.38 min at age 21, paused her career from age 24 to 31, and set a personal best at age 33 (in 2026) of 1:55.03 min. Her 14.13 s improvement from age 16 to 33 matches our calculated 90th percentile (Fig. 3E), likewise implying she reached her maximum. Overall, career-extending athletes often reach their personal bests beyond age 30, showing performance increases from youth to late senior age that match our calculated high performance gains (~90th percentile).

Finally, some athletes reach world-class levels unusually early. Although potential assessments for such early-blooming athletes might seem futile, one can still assume that their subsequent performance gains should be below average. A prime and forward-looking example is 800 m runner Cooper Lutkenhaus, who progressed from 1:47.58 min at 16 to 1:42.77 min at 17, and 1:42.08 min at 18—a 5.5 s improvement matching the 25th percentile of our calculation (**Fig. 3E**). Projecting a 50th–75th percentile gain (from ages 16 to 25) yields 1:37.64–1:40.49 min. However, achieving this requires improving his 46.3 s 400 m best (at age 17) to 44.2–45.5 s at the senior level, assuming that he maintains his unusually high KsA 400/800 m value of 0.905446 (92nd percentile). Incidentally, Lutkenhaus's high KsA value implies that he would translate a 45.3 s time to 1:39.99 min. Although such calculations appear to be back-of-the-envelope estimates, combining our performance corridors with the KsA approach provides a theoretical framework for such extreme performances.

Given the prominent examples of atypical career trajectories among world-class athletes, one might wonder whether they represent the rule rather than the exception at the elite level. Although robust statistics are lacking—partly because elite data would need to be contrasted with national or regional cohorts—this is unlikely. Instead, a saliency bias is probable, as such unusual paths are disproportionately featured in media and literature. Even if a non-negligible share of elite runners exhibit atypical progressions, the extreme cases discussed here demonstrate they can still be partly captured by combining our performance corridors with the

KsA approach. This suggests that even these exceptional athletes remain constrained by adaptability over time and pace change per distance change. These two key performance determinants possess a physiological foundation and are captured by our performance corridors and the KsA approach as integrative read-outs. Consequently, we propose that combining performance corridors with the KsA approach provides a reliable tool for roughly estimating the potential of unusual career paths, which in turn enables targeted training programming.

Beyond Performance Corridors: Event-switching athletes can be captured by the KsA approach and are useful for identifying potential world-class athletes

We highlight that our performance corridors are not useful for event-switchers, such as 400 m runners transitioning to the 800 m. These athletes occasionally show exceptional (initial) performances over the new main distance—regularly yet far from universally—largely driven by an unusually high performance level in the lower neighboring distance. Consequently, the performance corridors prove largely unhelpful for this group regarding the new main event, whereas applying the KsA approach offers a pragmatic solution. For instance, Femke Broeders-Bol ran the 400 m at age 16 in 54.95 s and at age 24 in 49.17 s, a performance increase of 5.78 s that corresponds to the calculated 90th percentile (**Fig. 3E**). At age 26, she entered her first 800 m season with a time of 1:54.71 min, which corresponds to the 19th KsA 400/800 m percentile (0.857292; [20]). Assuming she reaches a KsA percentile between 25 and 50 - maybe the 37th percentile (0.875067; [20]) - this projection yields an 800 m potential of 1:52.38 min, a performance that is extreme yet within the realm of possibility. Thus, while standard performance corridors are not suitable for estimating the potential of event-switching athletes, a pragmatic application of our KsA approach should be well-suited.

Given the frequent occurrence of successful event-switching, it is natural to adopt this approach and encourage athletes to test the next higher distance. From our perspective, event-switching offers a key leverage point for national sports federations to promote potential world-class athletes. To illustrate with women's 800-meter running: the 2026 ranking list of the German Athletics Association (DLV) features 10 athletes with 400-meter times between 50.57 and 52.63 seconds—performances that potentially enable them to run in the 1:55–1:57 minute range over 800 meters. Of course, we emphasize that only very few of these 400-meter runners will achieve such 800-meter times. Nevertheless, systematically applying this approach across all distances (e.g., 100m/200m to 400m, 400m to 800m, 800m to 1500m, 1500m to 3000m/5000m) and assuming a success rate of about 10% would unlock substantial world-class potential. We

acknowledge that, alongside physiological prerequisites, mindset, previous training background, and traditional club structures (rigid groupings of sprinters, middle-distance, and long-distance runners) present significant barriers. Nonetheless, national federations like the DLV hold the greatest strategic leverage through targeted funding guidelines and intelligent pre-selection. In this pre-selection process, expert coaching insight and performance diagnostics are crucial. Regardless of that, our KsA approach suggests that only exceptionally fast athletes on the respective lower adjacent distance stand a realistic chance of reaching world-class standards. This is especially true when assuming that the world-class level will continue to evolve in both depth and breadth.

The combined use of performance corridors and the KsA approach enables an estimation of a youth runner's performance potential with a reliability of about 3%

Based on the presented results and our previously published KsA approach [19–21], we propose a step-by-step procedure (**Fig. 7**) to estimate a youth runner's potential in a main event (e.g., 800 m). Of note, we emphasize that the proposed evaluation procedure presupposes that athletes undergo age-appropriate, performance-oriented, and structured training starting around age 16, with the ultimate goal of maximizing senior-level performance. Estimating runner´s potential requires at least three race times recorded across three distinct ages between 16 and 19, ideally over the main event as well as in the lower and upper neighboring distances.

First (steps 1 and 2, **Fig. 7**), youth times over the main event are assigned to the appropriate performance corridors and thus to potential age-specific target times. To this end, we have developed an open-source web application, which is accessible for male (https://leistungs-korridore-manner.replit.app) and female (https://leistungskorridore-frauen.replit.app). Next (steps 3 and 4, **Fig. 7**), based on the age-specific target times, the corresponding target values for the upper and lower neighboring distances are calculated based on our KsA values which is available for males and females. Finally (steps 5–7, **Fig. 7**), realistic age-specific target times for all three distances are established, training measures are derived, target times and training measures are adjusted annually based on achieved race times, and recovery, nutrition, mindset, environment, and other performance-determining cofactors are integrated into training programming. The scheme is illustrated using a female 800 m runner, showing that her potential is initially estimated at 1:54 based on performance corridors and then refined to 1:56 using the KsA approach.

Strengths and limitation of the study

A major strength of our study is the comprehensive compilation of longitudinal - rather than cross-sectional - data spanning diverse performance levels across six running distances, which are interrelated regarding physiological demands. We demonstrate that high variance in age-related performance gains is evident across every performance level, event distance, and both sexes. Explicitly accounting for this variance when deriving predictive performance corridors is - to the best of our knowledge - unique to this study. This enable us to foreshadow senior performance with an accuracy of about 3% using race times between ages 16 and 19. Furthermore, integrating our KsA approach allows us to refine the predictive corridors using performances from neighboring events. Overall, this framework yields a 7-step model for more reliable talent prediction than relying on age-related performances at a single event alone.

A limitation of our study is the relatively small sample size of KsA values for the 200m/400m and 400m/800m distance pairs. Specifically, youth athletes rarely contest both the 200m and 400m compared to the 100m/200m combination, while many 800m runners compete in the 400m only sporadically. Furthermore, our performance corridors assume a well-rounded, largely injury-free training history from age 16 onward. The applicability of the predictive performance corridors is further limited for early or late bloomers, cross-over athletes, or event switchers. However, our KsA approach provides a valuable evaluation tool for such cases. We would like to emphasize that although our analysis ends at age 25, further progression beyond this age is of course possible. Therefore, our performance corridors are left open-ended after this threshold, despite performance gains typically plateauing thereafter.

Conclusion

Our study provides age-related predictive performance corridors for running distances from 100m to 3,000m for both sexes, spanning from regional to international levels. When race times between ages 16 and 19 are known, the corridors predict senior performance with an accuracy of approximately 3%. This prediction can be further refined by using the KsA approach, which accounts for the performances in the neighboring distances related to the main event. The combination applied here - comprising (1) the use of longitudinal data, (2) the explicit consideration of performance gain variance, (3) the application of a weighted per-year time reduction approach, and (4) the integration of the KsA approach - is likely to be beneficial for talent identification and development in other sports, such as rowing or swimming.

Materials and Methods

Longitudinal performance data from GBR

Longitudinal performance data from GBR for males and females for the period 2015-2024, covering distances from 100 m to 3000 m, were retrieved from the *Power of 10* database (https://www.powerof10.uk), providing comprehensive athlete rankings across the United Kingdom. Both indoor and outdoor performances were included. For each year, distance, and sex approximately 1,000 performances (totaling ~120,000) were downloaded, encompassing all age groups from youth to senior levels up to predefined cut-off times of the database (e.g., 53.0 s for 400 m in males).

Following the merging of annual lists and subsequent data cleaning (e.g., age conversions), we identified runners for the analysis who achieved at least five performances in a specific distance (100 m to 3,000 m) between the ages of 16 and 25 (**Table S01 for males and Table S04 for females**). For each of the six distances, age-dependent performances were divided into two groups: Group I was composed such that the personal best performances achieved between the ages of 16 and 25 at the respective distances matched those achieved by German national-class runners. Group II comprised performances representing a lower performance level, categorized as regional-class runners. In both groups, approximately 20 to 60 runners were included for each distance.

We additionally identified athletes who recorded performances in two adjacent events (e.g., 100 m and 200 m) at the same age. These data were used to calculate KsA values for each runner, distance pair, and age (**Table S09 for males and Table S12 for females**). For a given distance pair, the analysis was restricted to athletes aged 16 to 25 who provided at least five KsA values over the 10-year period. However, for the male 200 m/ 400 m and 400 m/ 800 m distance pairs, the inclusion criteria were relaxed to a minimum of two KsA values per runner due to a more limited data pool. The number of runners included comprises approximately 15 to 25 per distance pair, with the exception of the male 200 m/400 m and 400 m/800 m distance pairs.

Longitudinal performance data from GER

Longitudinal performance data from GER are based on a re-analysis of data previously published by our group [19–21]. We screened the German annual outdoor top-30 lists from 1980 to 2022 for male and female runners ranked in two neighboring distances, ranging from 100

m/200 m to 1500 m/3000 m. The performance times of these runners were used to analyze the performance development for each distance from 100 m to 3,000 m across the age range of 16 to 25 years (**Table S02 for males and Table S05 for females**). For the 100-m and 200-m events, performance times of 100 m/200 m runners were used; for the 400 m event, 200 m/400 m runners; for the 800 m and 1500 m events, 800 m/1500 m runners; and for the 3000 m event, 1500 m/3000 m runners. Only runners with at least three recorded performances in each distance between the ages of 16 and 25 were included. Approximately 15 to 40 male and 15 to 30 female runners were included for each distance.

Performance times were additionally used to calculate individual KsA values for each runner, distance pair, and age (**Table S10 for males and Table S13 for females)**. The analysis was restricted to runners aged 16 to 25 who provided at least three KsA values over the 10-year period. However, for the 200 m/400 m and 400 m/800 m distance pairs of both sexes, the inclusion criteria were relaxed to a minimum of two KsA values per runner due to a more limited data pool. With the exception of the 200 m/400 m and 400 m/800 m distance pairs, approximately 15 to 30 runners were included for each distance.

Cross-sectional KsA values for age groups from GER

Cross-sectional KsA values were obtained from annual national top 30 lists from GER, stratified by sex and the age groups U18, U20, U23, and senior (**Table S11 for males and Table S14 for females**). This re-analysis was restricted to the period 1980–2009 and has been described previously [19]. To compare the data with the age-related data, the KsA values (mean, SD) for the age groups were assigned to the exact ages of 17 (U18), 19 (U20), 22 (U23), and 25 (senior). For each age group and distance pair, the number of male or female runners included in the calculations was at least 299 (100 m/200 m), 113 (200 m/400 m), 30 (400 m/800 m), 175 (800 m/1500 m), and 247 (1500 m/3000 m).

Longitudinal performance data from World Athletics All-time lists

The World Athletics database (www.worldathletics.org) was utilized to trace the performance development of the all-time top-10 runners (until 02/2026) for distances from 100 m to 3000 m between the ages of 16 and 25 (**Table S03 for males and Table S06 for females**).

Web applications to visualize and compare performance progressions

Open-source web applications ('apps') were developed for both male (https://leistungskorridore-manner.replit.app) and female (https://leistungskorridore-frauen.replit.app) runners. These applications visualize individual performance progression across distances from 100 m to 3,000 m. They compare individual results with performance corridors (green, yellow, and red areas) corresponding to different target times (**Fig. 4**). The outer boundaries of these corridors represent the 25th and 90th percentiles, respectively, of performance gains from age 16 to 25 and throughout subsequent years (**Fig. 3E**). The upper and lower boundaries represent large and small performance gains, respectively.

Web applications to calculate KsA values and corresponding percentiles

The background, the concept, the calculation, and several applications of our KsA approach has been extensively described [19–21]. More recently, open-source web applications ('apps') have been developed for both male (https://ksawerte.com) and female (https://runner-index-1-prinzfrank.replit.app) runners to calculate KsA values and their corresponding percentiles. These apps were used to exemplify the proposed evaluation scheme for runners (**Tab. 3, Fig. 7**), combining the performance corridors with the KsA approach.

Calculations and statistical analysis

Standard procedures. Performance times given in minutes (800 m to 3000 m) were converted into seconds with two decimal places. KsA values were calculated by dividing the pace of the shorter neighboring distance (s/100 m) by the pace of the longer neighboring distance (s/ 100 m) within a specific distance pair (e.g. 100 m/200 m). KsA values were reported to six decimal places. Calculations of performance times and KsA values were performed in Microsoft Excel. The resulting data were then transferred to GraphPad Prism for statistical analysis and graph generation. Descriptive statistics (e.g., standard deviation, interquartile range) were calculated using standard formulae.

Statistical analysis of running times and KsA values. Age-dependent running times (**Figs. 1 and 2**) as well as KsA values (**Figs. 5 and 6**) were compared - separately for each distance and sex -pairwise between the four groups (e.g., 100 m male: the 9.76 s, 10.41 s, 10.38 s, and 10.79 s groups; **Fig. 1A**) at each age (16–25 years) using two-sided Welch's t-tests. P-values were adjusted for multiple comparisons using the Holm-Bonferroni method (six comparisons per age). Differences were considered statistically significant at an adjusted p-value < 0.001.

Calculation of performance gains and performance corridors. To calculate performance gains from ages 16 to 25, we compiled data across distances from 100 m to 3000 m for male national runners from GBR (**Table S01**) and GER (**Table S02**), world-class runners (**Table S03**), and all female groups (**Tables S04–S06**). Performance gains were determined by calculating the difference between the fastest and slowest times achieved by each runner between ages 16 and 25. The resulting improvements for each runner, distance, and sex (**Table S07**) were plotted (**Fig. 3C/D**), and corresponding percentiles were calculated (**Fig. 3E**). Finally, the time improvements represented by the percentiles were used to calculate age-dependent times for specific target times (**Table S08**; e. g. target times for 100 m: 9.80, 10.10, 10.40 s). This calculation was utilized for the web applications for each sex featuring performance corridors for the specific targeted times. Because several runners reach their personal bests after the age of 25, we mapped the performance corridors up to the age of 35.

Calculation and statistical analysis of performance gain percentiles. The data on the performance gains of all runners (regional to international level; **Fig. 3C/D, Table S07**) for each distance and sex were tested separately using the Shapiro-Wilk test with a significance threshold of $p < 0.01$. The tests revealed significant deviations from a normal distribution for females in the 100 m to 800 m events, whereas the other groups showed no significant deviations from normality. To present the performance gains uniformly across all distances and both sexes, we calculated the corresponding percentiles (25th, median, 75th, and 90th) using linear interpolation. This method calculates the position of the desired percentile based on the rank ($R = p*(n+1)/100$, where p is the percentile and n is the number of data points). If the rank R is not an integer, interpolation is performed between the adjacent rank positions.

Calculation and statistical analysis of theoretical age-dependent trajectories. To calculate theoretical progression trajectories from ages 16 to 25, we used a weighted per-year time reduction approach introduced by Coe and Martin [22]. For each distance, the total time improvement (in seconds, e.g., 10 seconds) obtained from the percentiles between ages 16 and 25 (**Fig. 3E**) was applied: For each consecutive year, the remaining years until the target age were determined (e.g., 25 - 16 = 9, 25 - 17 = 8, down to 25 - 24 = 1). The total time improvement was then divided by the sum of these remaining years (e.g., 10 / 45 = 0.22). Multiplying this constant by the respective remaining years yielded the weighted annual improvement (e.g., 0.22 * 9 = 1.98 s improvement from age 16 to 17; 0.22* 8 = 1.76 s from age 17 to 18, down to 0.22 * 1 = 0.22 s from age 24 to 25). This proportional weighting scheme yields a geometric function,

resulting in a relatively smooth trajectory. As an example, analysis between empirical and theoretical 1500 m times (Fig. 3A, 3:27.8 min group) was assessed using an equivalence test (Two One-Sided Tests, TOST) with predefined equivalence margins of ±8 seconds. P-values were adjusted for multiple comparisons using the Holm-Bonferroni method, with statistical significance set at an adjusted $p < 0.001$. Statistical equivalence between empirical and theoretical values was demonstrated at 9 of 10 ages (16 and 18–25 years; Holm-adjusted $p < 0.001$). Only at age 17 could equivalence not be established (adjusted $p = 0.0033$).

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Author contributions

W. B. and F. D. analysed the data, prepared the figures and tables, wrote the manuscript text, and reviewed the manuscript.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files (**Tables S1–S14**).

Competing interests

The authors declare no competing interests.

Figure legends

Fig. 1. Performance times (seconds, mean ± SD) for 100m (**A**), 200m (**B**), 400m (**C**), 800m (**D**), 1500m (**E**), and 3000m (**F**) events from ages 16 to 25, derived from male runners on the Top 10 all-time lists (-■-), as well as annual national lists for GER (-○-) and GBR (-□-, -♦-). The specified times in the legends (e. g. 9.76) are personal bests achieved by the runners between the ages of 16 and 25. Statistical analysis: For each distance, running times were compared pairwise between the four groups at each age (16–25 years) using two-sided Welch's t-tests, adjusted for multiple comparisons. For all distances, group 1 (e. g., 9.76 s) showed significantly ($p < 0.001$) faster running times than group 4 (e. g., 10.79 s) from age 16–18 onward normally. Running times of groups 2 and 3 (e. g., 10.41 vs. 10.38 s) were not significantly different at any age. Comparisons between group 1 vs. group 2, 1 vs. 3, 4 vs. 2, and 4 vs. 3 revealed partial significances depending on age, whereas significant differences were consistently calculated when standard deviations did not overlap. Underlying datasets: Table S01 (GBR), S02 (GER), and S03 (Top 10 all-time).

Fig. 2. Performance times (seconds, mean ± SD) for 100m (**A**), 200m (**B**), 400m (**C**), 800m (**D**), 1500m (**E**), and 3000m (**F**) from ages 16 to 25, derived from female runners on the Top 10 all-time lists (-■-), as well as annual national lists for GER (-○-) and GBR (-□-, -♦-). The specified times in the legends (e. g. 10.95) are the personal bests achieved by the runners between the ages of 16 and 25. Statistical analysis: For each distance, running times were compared pairwise between the four groups at each age (16–25 years) using two-sided Welch's t-tests, adjusted for multiple comparisons. For all distances and similar to the statistical analysis of males runners (Fig. 1), group 1 (e. g., 10.95 s) showed significantly ($p < 0.001$) faster running times than group 4 (e. g., 12.17 s) from age 16–18 onward normally. Running times of groups 2 and 3 (e. g., 10.39 vs. 10.39 s) were not significantly different at any age. Comparisons between group 1 vs. group 2, 1 vs. 3, 4 vs. 2, and 4 vs. 3 revealed partial significances depending on age, whereas significant differences were consistently calculated when standard deviations did not overlap. Underlying datasets: Table S04 (GBR), S05 (GER), and S06 (Top 10 all-time).

Fig. 3. Empirical and theoretical performance trajectories in the 1,500 m (**A**, male) and 800 m (**B**, female) events from ages 16 to 25. Performance times (seconds, mean ± SD) in the 1,500 m and 800 m events were derived from groups of runners. The corresponding theoretical progression trajectories were derived from the Coe/Martin approach. An equivalence test

adjusted for multiple comparisons was used to analyze the 3:27.8 min group with the theoretical trajectory. It revealed statistical equivalence for 9 out of 10 ages (16 and 18–25 years; adjusted $p < 0.001$). Only at age 17 could equivalence not be established ($p = 0.0033$). Distribution (individual data points, medians, interquartile ranges) of performance improvements (in seconds) for male (M) and female (F) runners from ages 16 to 25 in the 100 m (100M: 100m male), 200m, and 400m (**C**) and the 800 m, 1500 m, and 3000 m (**D**) events. Performance improvements (in seconds) across distances form 100 m (100-M: 100m male) to 3000 m events were stratified by percentiles (**E**). Data on performance improvements (C-E) were obtained by compiling records from world-class runners as well as national runners from GER and GBR. Performance improvement was defined as the difference between the fastest and slowest times a runner achieved between the ages of 16 and 25 years. Underlying datasets: Table S02 (3:38.5), S03 (3:27.8), S04 (2:12.02), S05 (2:03.4), S07 (C-E).

Fig. 4. Screenshots of the web application for 1500 m male (**A**) and 800 m female (**B**) runners showing performance corridors (green, yellow, and red areas) corresponding to different target times. The performance trajectories of three individual male runners (AM, AD, JK) and three female runners (TS, JB, AW) were plotted as examples. The outer boundaries of the respective performance corridors represent the 25th and 90th percentiles of performance improvement between the ages of 16 and 25, with the upper boundary representing the greater performance improvement. The web applications are published at the following URLs: https://leistungskorridore-manner.replit.app and https://leistungskorridore-frauen.replit.app. Underlying datasets: Table S08.

Fig. 5. KsA values (mean ± SD) for the distance pairs 100m/200m (**A**), 200m/400m (**B**), 400m/800m (**C**), 800m/1500m (**D**), and 1500m/3000m (**E**) from ages 16 to 25, derived from male runners on the annual national lists for GBR (-■-) and GER (-▲-). KsA values for the age categories (-●-) U18 (data point: 17 years), U20 (19 years), U23 (22 years), and Senior men (25 years) were obtained by separate analysis of annual national lists for GER stratified by age groups. Statistical analysis: For each distance, KsA values were compared pairwise between the three groups (GBR, GER, age groups) using two-sided Welch's t-tests, adjusted for multiple comparisons. For all distances, KsA values between the groups were not significantly ($p > 0.001$) different at any age. Underlying datasets: Table S09 (GBR), S10 (GER), and S14 (age groups, GER).

Fig. 6. KsA values (mean ± SD) for the distance pairs 100m/200m (**A**), 200m/400m (**B**), 400m/800m (**C**), 800m/1500m (**D**), and 1500m/3000m (**E**) from ages 16 to 25, derived from female runners on the annual lists for GBR (-■-) and GER (-▲-). KsA values for the age categories (-●-) U18 (data point: 17 years), U20 (19 years), U23 (22 years), and Senior women (25 years) were obtained by separate analysis of annual national lists for GER stratified by age groups. Statistical analysis: For each distance, KsA values were compared pairwise between the three groups (GBR, GER, age groups) using two-sided Welch's t-tests, adjusted for multiple comparisons. For all distances, KsA values between the groups were not significantly ($p > 0.001$) different at any age. Underlying datasets: Table S12 (GBR), S13 (GER), and S14 (age groups, GER).

Fig. 7. Scheme for estimating youth runners' potential over a main distance using performance corridors and the KsA approach. To provide a solid estimation of a youth runner's potential at a main distance (e.g., 800 m) for later performance at the senior level, at least three race times between the ages of 16 and 19 are necessary. Step 1: Estimation of senior-level performance at the main distance by mapping youth times to the respective corridors. Step 2: Extraction of age-specific target times for the main distance from the performance corridors of Step 1. Steps 3 and 4: KsA-based calculation of age-specific times for the lower (e.g., 400 m) and upper (e.g., 1500 m) neighboring distances, respectively. Step 5: Setting realistic age-specific target times up to age 25 for the main and neighboring distances based on Steps 1–4, as well as youth performances over the lower and upper neighboring distances. Step 6: Annual adjustment of target times and training measures based on achieved race times. Step 7: Integration of recovery, nutrition, mindset, environment, and other performance-determining cofactors into training programming. The scheme is illustrated using a female 800 m runner with an estimated potential of 1:56 min at the senior level. The age-specific times for the lower and upper neighboring distances of this prototypical 800 m runner were derived from the age-specific times over the main distance and KsA values (400/800 m and 800/1500 m) corresponding to the 75th and 25th percentiles, respectively. These percentiles were chosen because world-class female 800 m runners typically achieve such KsA values. KsA, coefficient of special endurance.

Tab. 1. Description of Datasets used for Analysis

name	GBR data	GER data	World data
supplementary tables	S01/04/09/12	S02/05/10/11/13/14	S03/06
data used for	Fig. 1-3, 5, 6	Fig. 1-3, 5, 6	Fig. 1-3
country/area	GBR	GER	world
type of ranking	annual best lists	annual best lists	all-time lists
time period	2015-2024	1980-2022	until 02/2026
depth of analysis	~1000 every year	first 30 every year	first 10

Tab. 2. Assignment of reported performance gains from youth to senior level using the percentiles proposed in this study

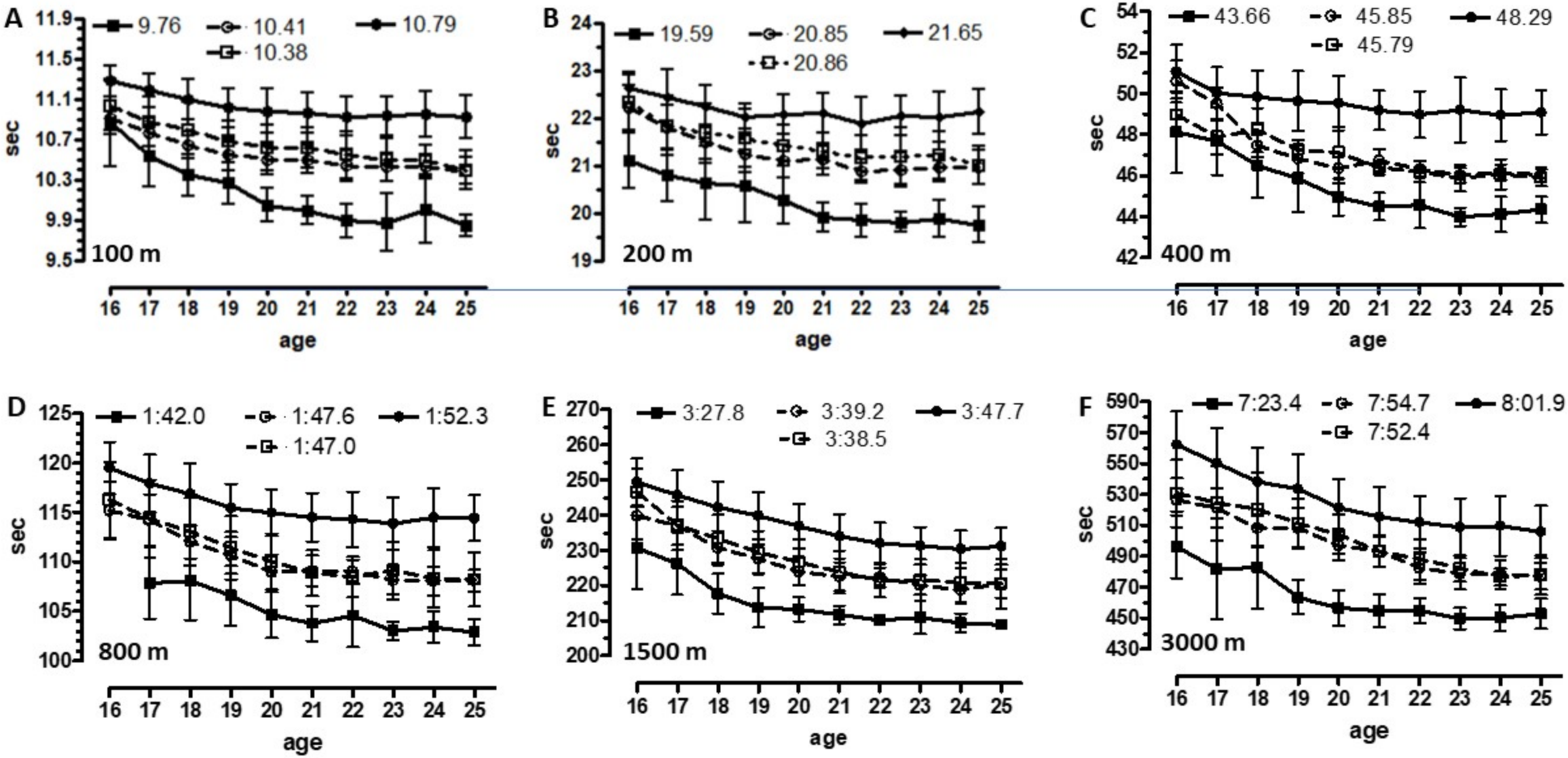
literature[a]	sex	event (m)	level[b] (s; min)	increase[c] (s)	this study[d] (percentile)
Gorzi et al., 2022	M	100	9.97	0.85	~90
ages 16-25	M	400	44.95	2.70	~50
	M	800	1:43.57	9.63	~75
	M	1500	3:32.40	15.60	~25
	F	100	11.07	0.69	~50
	F	400	49.89	3.40	~50
	F	800	1:58.28	10.62	~75
	F	1500	4:00.60	16.80	~25
Boccia et al., 2021	M	100	~10.00	~0.55	~50
ages 16-25	M	400	~44.20	~2.60	~50
U18 and senior level[e]	F	100	~10.90	~0.65	~50
	F	400	~51.00	~2.00	~25
Boccia et al., 2021	M	100	~10.00	~0.60	~50
ages 16-25	M	400	~45.00	~3.20	~50
senior level[f]	F	100	~11.10	~0.70	~50
	F	400	~51.00	~3.50	~50
Agudo-Ortega et al., 2024	M	100	~10.50	~0.45	~25
Ages 16-25	M	100	~10.98	~0.57	~50
	F	100	~11.70	~0.50	~25
	F	100	~12.20	~0.30	~25
Weippert et al., 2020	M	800	1:47.06	13.52	~90
ages 16-22	M	1500	3:38.38	28.19	~90
	F	800	2:01.54	12.63	~90
	F	1500	4:07.34	25.09	~90

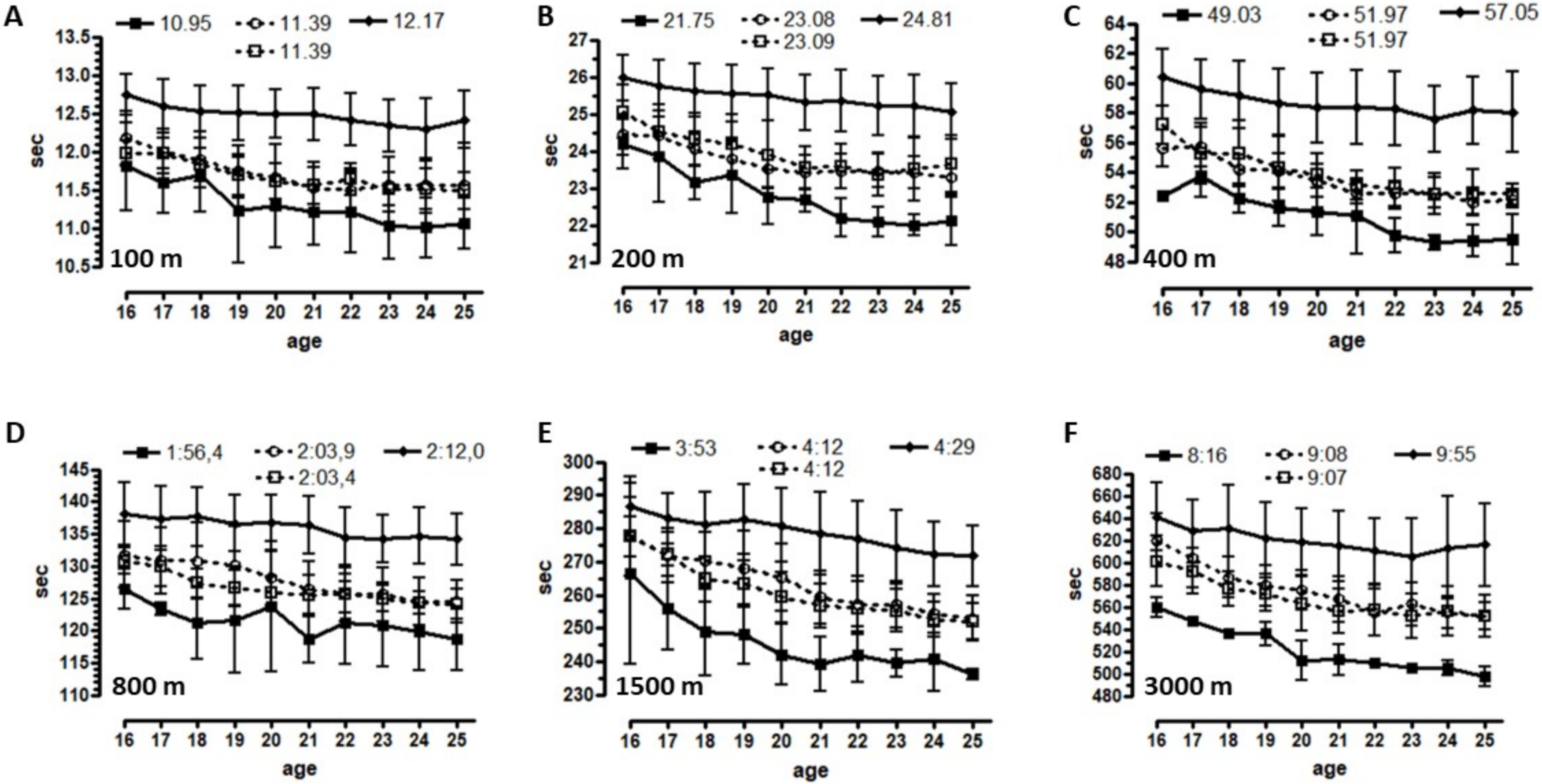
[a]Literature source and investigated age range are indicated. [b]Mean performance level at age 25 of the investigated runners. Race times were extracted from the respective literature tables (exact times are given) or figures (approximate times are given). [c]The increase in seconds (s) refers to the mean performance improvement across the specified age range. [d]Assignment of the performance improvements (based on exact or approximate times) identified in the literature to the percentiles determined in the present study regarding performance progression from age 16-25 (Fig. 3E). For example (row 1), an increase of 0.85 seconds over 100 m for males from ages 16 to 25 corresponds to the 90th percentile in our study. [e]Runners ranked at both the U18 and senior levels. [f]Runners ranked exclusively at the senior level. M, male; F, female.

Tab. 3. Comparison of exemplary runner performances with calculated age-related times over 400 m and 800 m targeting 1:54 and 1:58 min

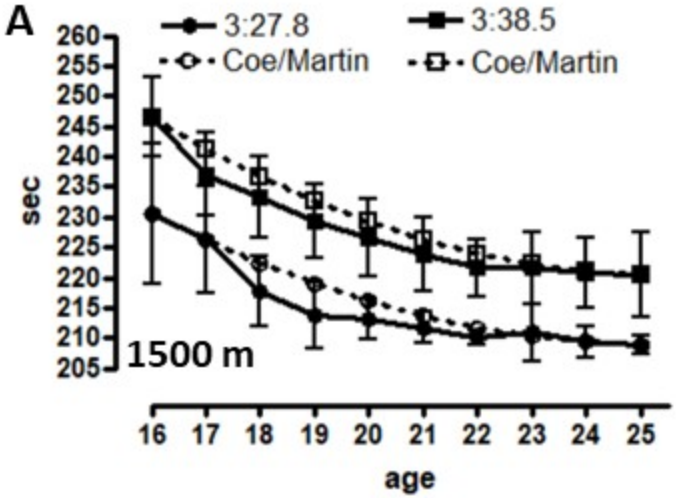
	target time 1:54.0[a]		Runner A[c]		Runner B[c]		target time 1:58.0[a]	
age	800 m (≤ min)	400 m[b] (range, sec)	800 m (min)	400 m (sec)	800 m (min)	400 m (sec)	800 m (≤ min)	400 m[b] (range, sec)
16	2:08.7	53.6-57.5	2:08.7	54.7	2:05.0	54.8	2:12.8	55.4-59.3
17	2:05.8	53.1-56.2	2:02.3	53.7	2:02.9	54.9	2:09.8	54.8-58.0
18	2:03.2	52.6-55.0	1:59.5	53.0	2:01.9	54.9	2:07.2	54.4-56.8
19	2:00.9	52.2-54.0	1:58.1	53.3	1:59.6	nd	2:04.9	54.0-55.8
20	1:58.9	51.8-53.1	1:57.8	52.7	1:59.1	53.8	2:02.9	53.6-54.9
21	1:57.3	51.5-52.4	1:55.9	51.0	na	na	2:01.3	53.3-54.2
22	1:56.0	51.3-51.8	1:53.7	50.8	na	na	2:00.0	53.1-53.6
23	1:55.0	51.1-51.4	na	na	na	na	1:59.0	52.9-53.2
24	1:54.3	51.0-51.1	na	na	na	na	1:58.3	52.8-52.9
25	1:54.0	50.9	na	na	na	na	1:58.0	52.7

Times were rounded to the nearest tenth of a second. nd, no data; na, not applicable, because runners had not reached the respective age by the time of publication. [a]The 800 m times for ages 16 to 25 for the specified performance corridors (1:54.0, 1:58.0 min) represent minimum times that should be achieved at the corresponding age. They match the 90th percentile (Fig. 3E), indicating a high-level performance progression. [b]The 400 m time ranges were calculated based on the age-related 800 m times targeting 1:54 and 1:58, respectively, and the assumption that female runners reach a KsA 400/800 m value of 0.893546, corresponding to the 75th percentile (199). [c]The race times of runners A and B are real-world data from extraordinary world-class (A) and national-level (B) female 800 m runners.

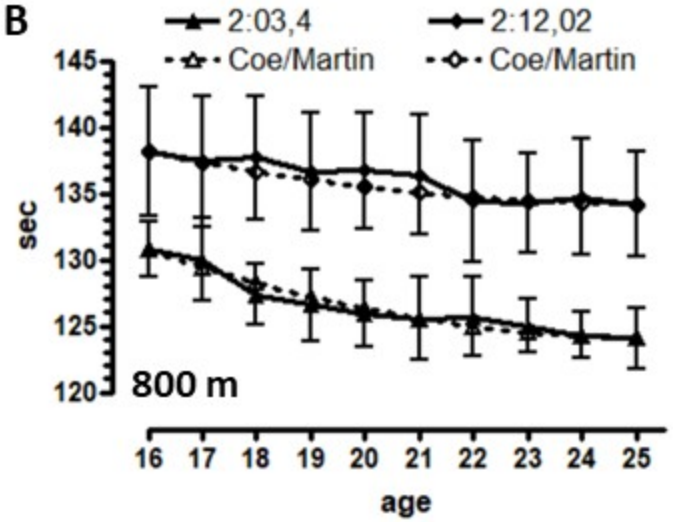

A
9.76
10.41
10.79
10.38
sec
100 m
age
B
19.59
20.85
21.65
20.86
sec
200 m
age
C
43.66
45.85
48.29
45.79
sec
400 m
age
D
1:42.0
1:47.6
1:52.3
1:47.0
sec
800 m
age
E
3:27.8
3:39.2
3:47.7
3:38.5
sec
1500 m
age
F
7:23.4
7:54.7
8:01.9
7:52.4
sec
3000 m
age


A
10.95
11.39
12.17
11.39
sec
100 m
age
B
21.75
23.08
24.81
23.09
sec
200 m
age
C
49.03
51.97
57.05
51.97
sec
400 m
age
D
1:56,4
2:03,9
2:12,0
2:03,4
sec
800 m
age
E
3:53
4:12
4:29
4:12
sec
1500 m
age
F
8:16
9:08
9:55
9:07
sec
3000 m
age

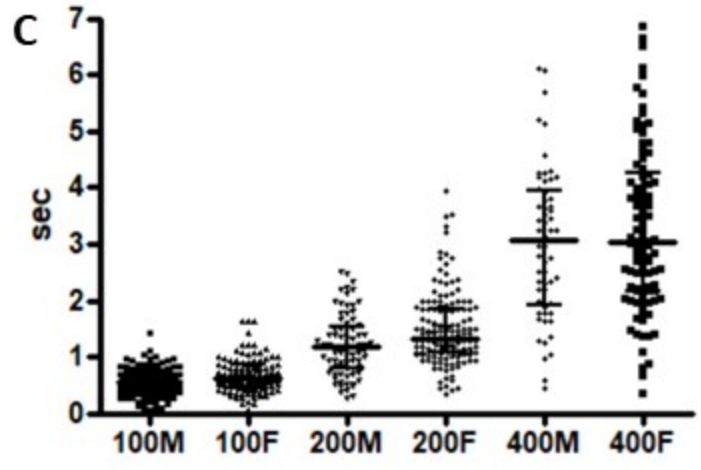
A



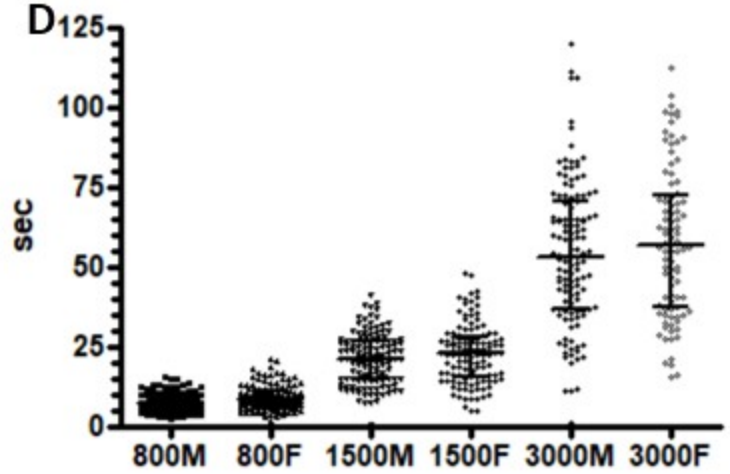
B



C



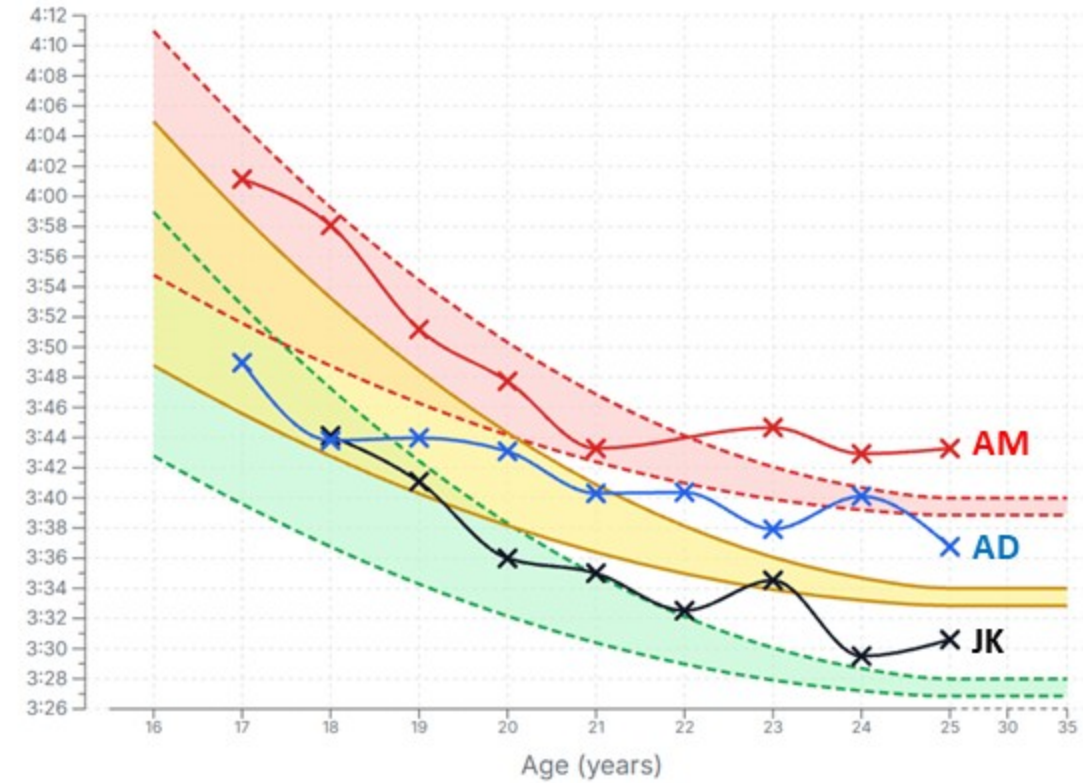
D



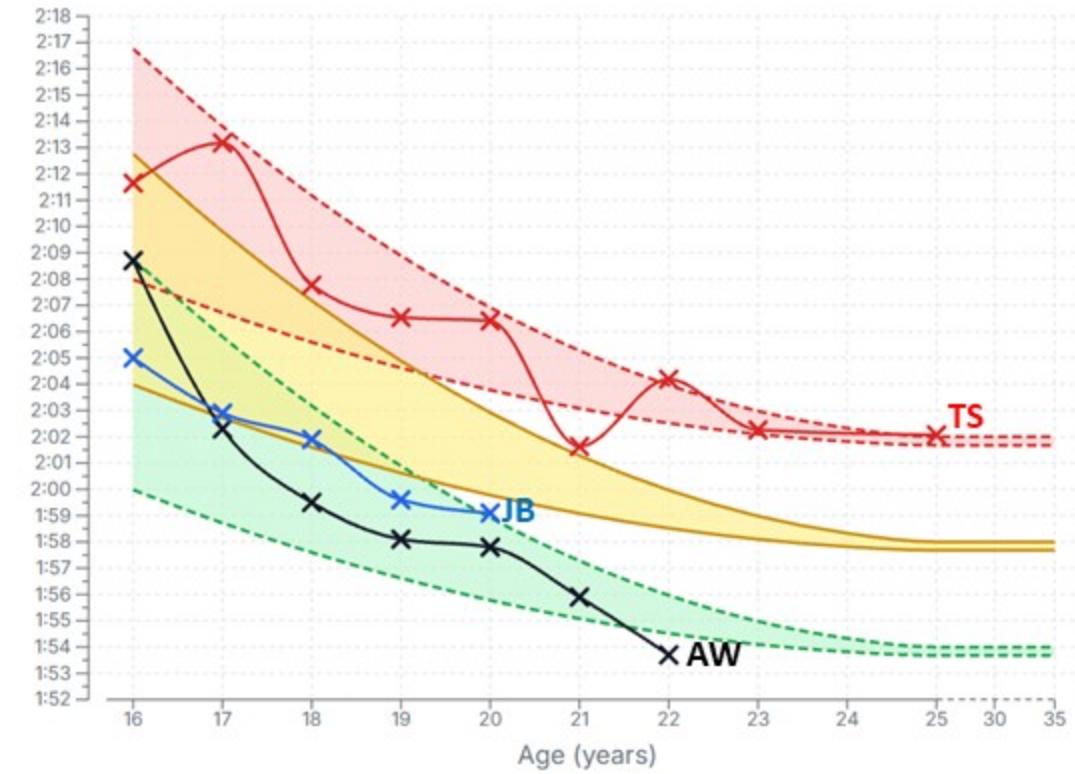
E

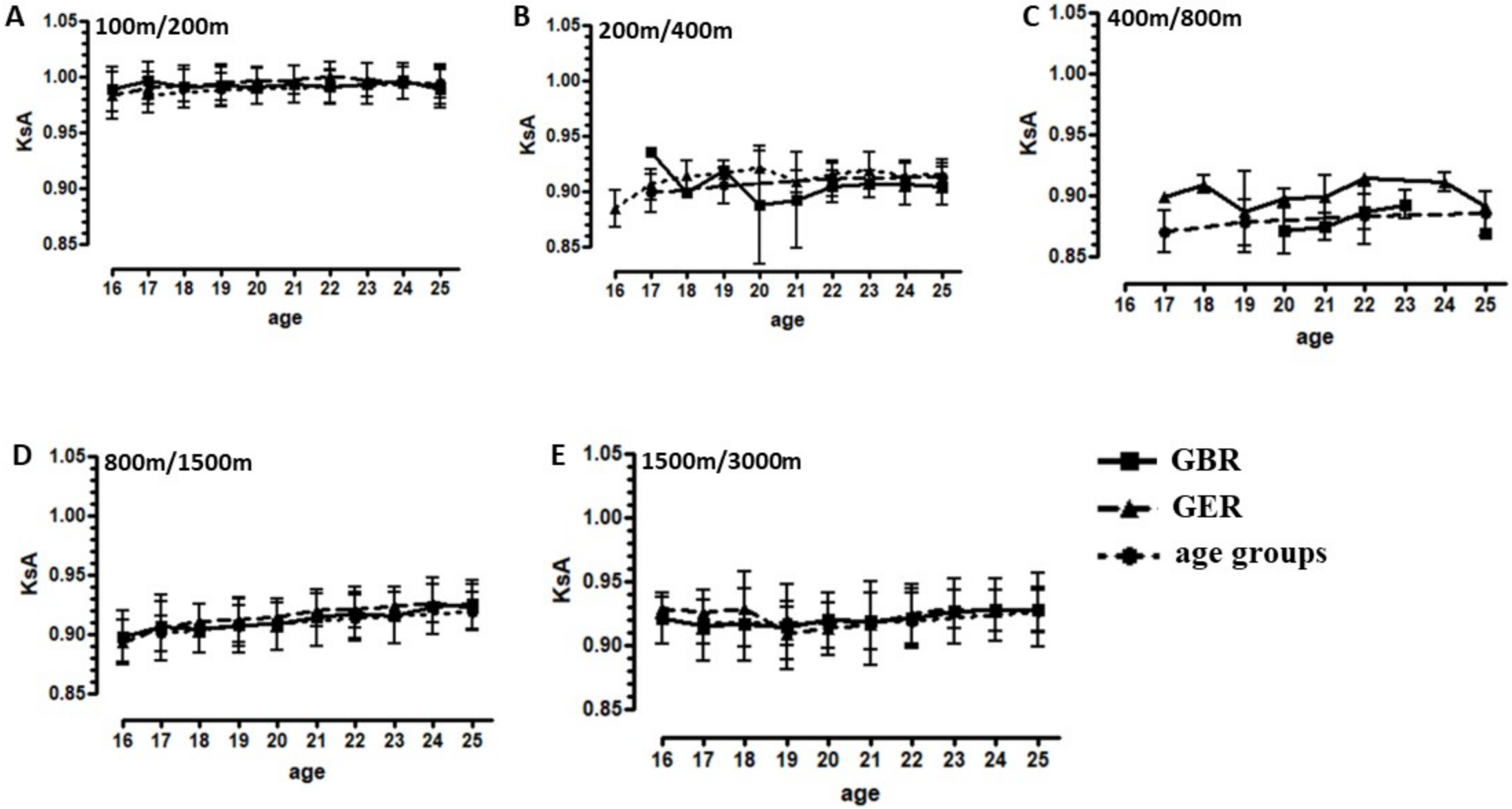
	percentile			
	25.	50.	75.	90.
100M	0.40	0.56	0.70	0.85
200M	0.81	1.17	1.50	1.99
400M	1.90	3.07	3.87	4.38
800M	5.31	7.09	9.94	12.54
1500M	14.78	21.35	26.80	30.97
3000M	37.50	52.91	67.37	81.22
100F	0.47	0.62	0.83	1.06
200F	1.07	1.31	1.85	2.31
400F	2.18	3.05	4.23	5.66
800F	5.98	8.39	10.90	14.76
1500F	15.63	23.21	27.66	35.11
3000F	37.28	56.60	71.94	90.93

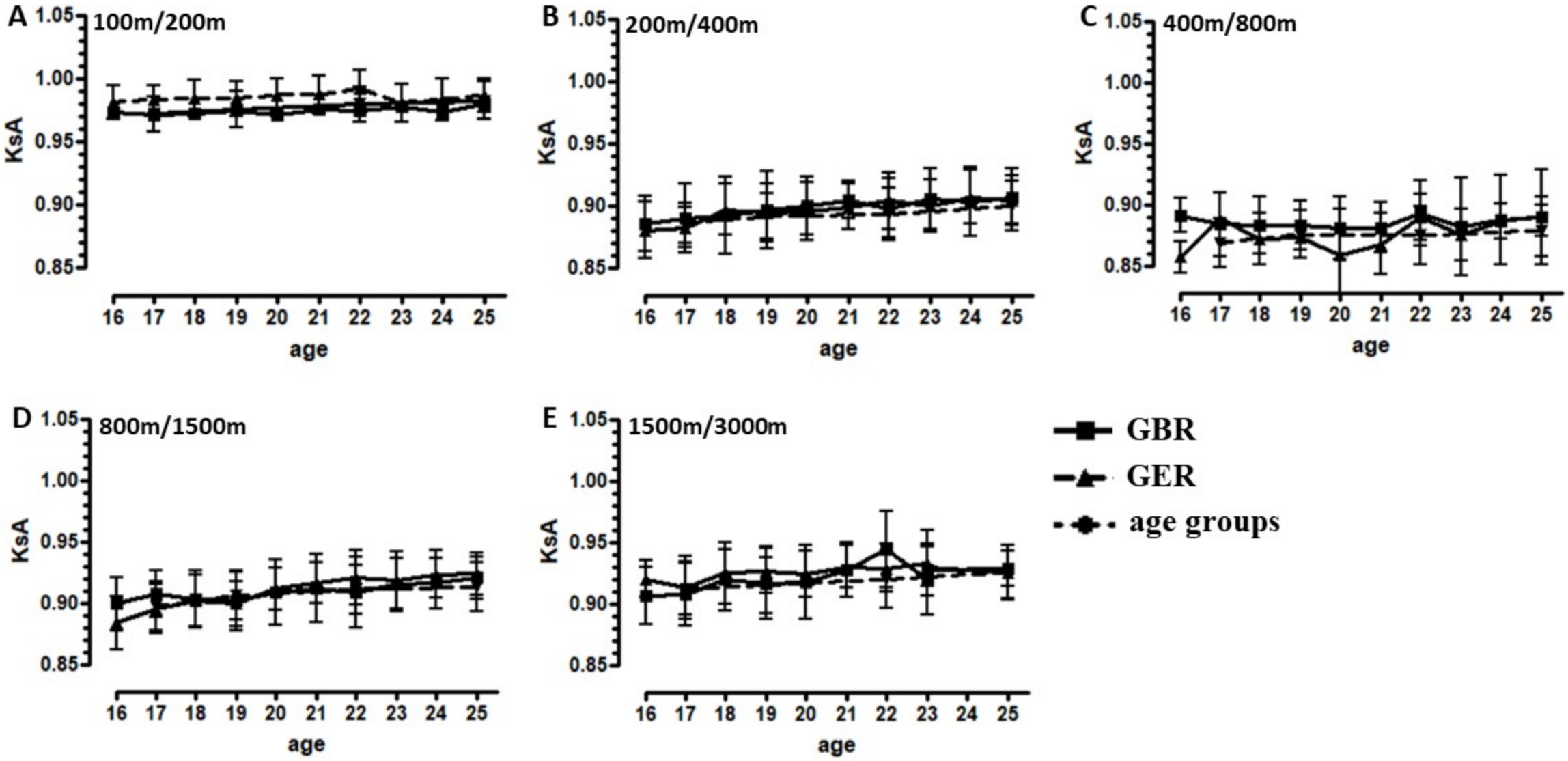
A

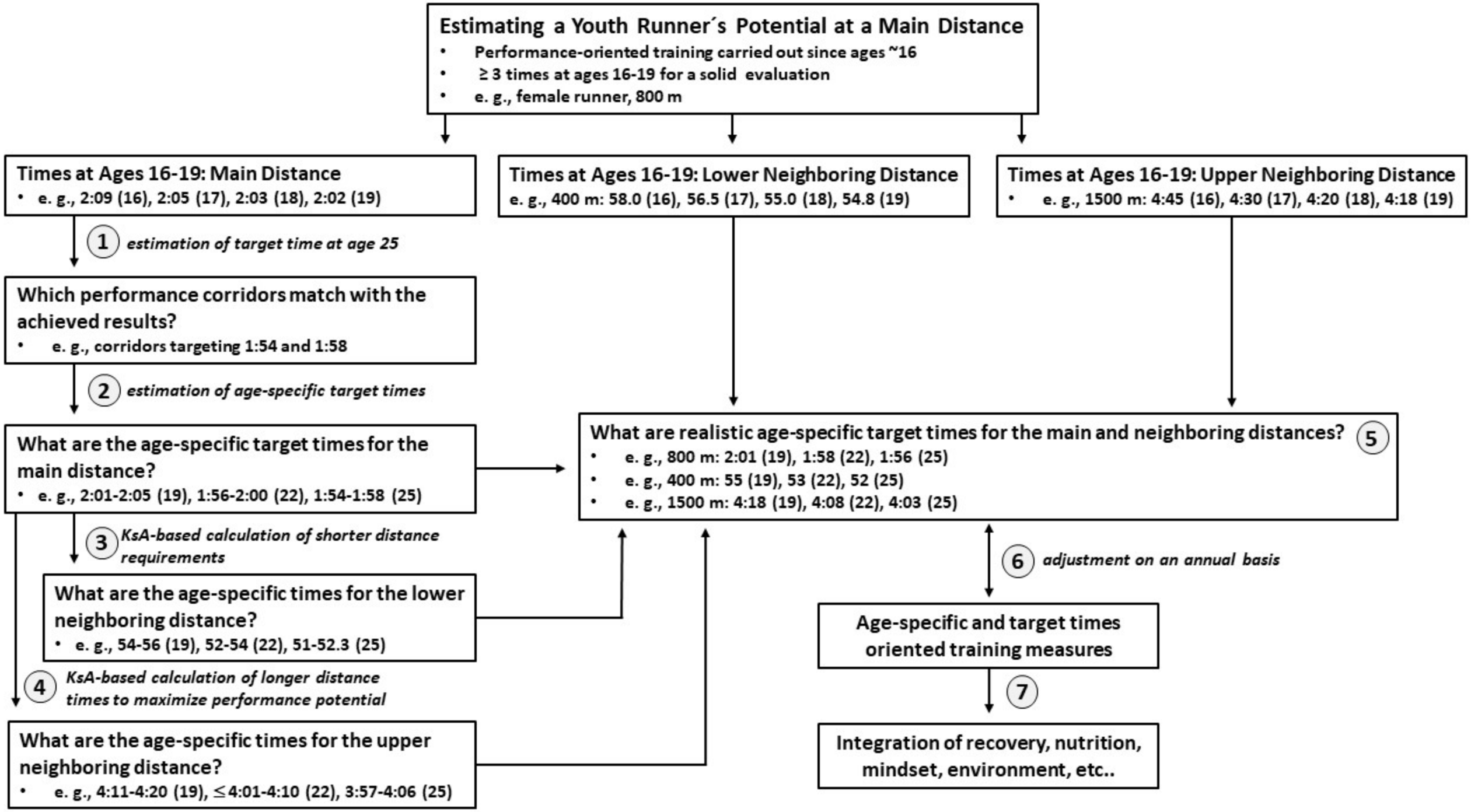

1500m (min:sec)
4:12
4:10
4:08
4:06
4:04
4:02
4:00
3:58
3:56
3:54
3:52
3:50
3:48
3:46
3:44
3:42
3:40
3:38
3:36
3:34
3:32
3:30
3:28
3:26
16
17
18
19
20
21
22
23
24
25
30
35
Age (years)
AM
AD
JK

B


800m (Min:Sek)
2:18
2:17
2:16
2:15
2:14
2:13
2:12
2:11
2:10
2:09
2:08
2:07
2:06
2:05
2:04
2:03
2:02
2:01
2:00
1:59
1:58
1:57
1:56
1:55
1:54
1:53
1:52
16
17
18
19
20
21
22
23
24
25
30
35
Age (years)
TS
JB
AW


A
100m/200m
B
200m/400m
C
400m/800m
D
800m/1500m
E
1500m/3000m
KsA
1.05
1.00
0.95
0.90
0.85
16 17 18 19 20 21 22 23 24 25
age
GBR
GER
age groups


A
100m/200m
B
200m/400m
C
400m/800m
D
800m/1500m
E
1500m/3000m
KsA
1.05
1.00
0.95
0.90
0.85
16 17 18 19 20 21 22 23 24 25
age
GBR
GER
age groups


Estimating a Youth Runner´s Potential at a Main Distance
• Performance-oriented training carried out since ages ~16
• ≥ 3 times at ages 16-19 for a solid evaluation
• e. g., female runner, 800 m
Times at Ages 16-19: Main Distance
• e. g., 2:09 (16), 2:05 (17), 2:03 (18), 2:02 (19)
Times at Ages 16-19: Lower Neighboring Distance
e. g., 400 m: 58.0 (16), 56.5 (17), 55.0 (18), 54.8 (19)
Times at Ages 16-19: Upper Neighboring Distance
• e. g., 1500 m: 4:45 (16), 4:30 (17), 4:20 (18), 4:18 (19)
1 estimation of target time at age 25
Which performance corridors match with the achieved results?
• e. g., corridors targeting 1:54 and 1:58
2 estimation of age-specific target times
What are the age-specific target times for the main distance?
• e. g., 2:01-2:05 (19), 1:56-2:00 (22), 1:54-1:58 (25)
What are realistic age-specific target times for the main and neighboring distances? 5
• e. g., 800 m: 2:01 (19), 1:58 (22), 1:56 (25)
• e. g., 400 m: 55 (19), 53 (22), 52 (25)
• e. g., 1500 m: 4:18 (19), 4:08 (22), 4:03 (25)
3 KsA-based calculation of shorter distance requirements
What are the age-specific times for the lower neighboring distance?
• e. g., 54-56 (19), 52-54 (22), 51-52.3 (25)
6 adjustment on an annual basis
Age-specific and target times oriented training measures
4 KsA-based calculation of longer distance times to maximize performance potential
What are the age-specific times for the upper neighboring distance?
• e. g., 4:11-4:20 (19), ≤4:01-4:10 (22), 3:57-4:06 (25)
7
Integration of recovery, nutrition, mindset, environment, etc..