Tracking Career Performance of Successful Triathletes

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ABSTRACT

MALCATA, R. M., W. G. HOPKINS, and S. N. PEARSON. Tracking Career Performance of Successful Triathletes. *Med. Sci. Sports Exerc.*, Vol. 46, No. 6, pp. 1227–1234, 2014. **Purpose**: Tracking athletes' performances over time is important but problematic for sports with large environmental effects. Here we have developed career performance trajectories for elite triathletes, investigating changes in swim, cycle, run stages, and total performance times while accounting for environmental and other external factors. **Methods**: Performance times of 337 female and 427 male triathletes competing in 419 international races between 2000 and 2012 were obtained from triathlon.org. Athletes were categorized according to any top 16 placing at World Championships or Olympics between 2008 and 2012. A mixed linear model accounting for race distance (sprint and Olympic), level of competition, calendar-year trend, athlete's category, and clustering of times within athletes and races was used to derive athletes' individual quadratic performance trajectories. These trajectories provided estimates of age of peak performance and predictions for the 2012 London Olympic Games. **Results**: By markedly reducing the scatter of individual race times, the model produced well-fitting trajectories suitable for comparison of triathletes. Trajectories for top 16 triathletes showed different patterns for race stages and differed more among women than among men, but ages of peak total performance were similar for men and women (28 ± 3 yr, mean ± SD). Correlations between observed and predicted placings at Olympics were slightly higher than those provided by placings in races before the Olympics. **Conclusions**: Athletes' trajectories will help identify talented athletes and their weakest and strongest stages. The wider range of trajectories among women should be taken into account when setting talent identification criteria. Trajectories offer a small advantage over usual race placings for predicting men's performance. Further refinements, such as accounting for individual responses to race conditions, may improve utility of performance trajectories. **Key Words:** CAREER TRAJECTORIES, MODELING, MONITORING, PROGRESSION, AGE OF PEAK PERFORMANCE, PREDICTION

In the elite sport environment, the monitoring of athletes' competition performances provide valuable information for guiding training programs, setting performance goals, and selecting talented athletes. For sports with consistent race environments, such as swimming, competition results offer a relatively reliable measure of athlete's ability. However, in many sports competition, results are affected by external factors, and an athlete's ability should be estimated using appropriate models to account for the extra variation on performances arising from such factors. Triathlon, consisting of swim, bike, and run race stages, is a particular example of a sport where a variety of environmental factors (temperature, wind, and race course profile) influence race conditions and, consequently, performance outcomes.

Triathlon performance is affected by environmental conditions. Windy or wet conditions result in slower times across all three triathlon stages (swim, cycle, and run), but other conditions can affect one stage in particular. For example, temperature determines whether it is a wetsuit swim, and the buoyancy of the wetsuits results in faster swim times (7). Race courses are another source of variation of performance times. Swim courses vary in geometry (buoy distance and configuration), water current, and whether the water is fresh or salty; cycle and run courses vary in elevation and number of sharp curves, and even the distance of the cycle stage can vary up to 10% of the standard 40 km (15). These environmental effects should be taken into account when assessing triathletes' performances.

Studies in age-related performance changes in triathlon have been performed mainly by Lepers et al. (3,9,19,26,30). For Olympic distance triathlon, effects of age and sex were analyzed using mean times of top triathletes. Although this approach provided an important general understanding of age and sex differences in triathlon performance, a different approach is needed to monitor individual athletes over time.

The analysis of long-term career changes in performance of individual athletes using competition results has been

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developed for track-and-field athletics (4,13,30), swimming (2,4,22), skeleton (5), and cross-country skiing (1). Bullock and Hopkins (5) developed individual performance trajectories for a 4-yr Olympic cycle, using a linear model to adjust for widely different race times arising from weather and course profiles. Hollings et al. (13) estimated specific environmental and other venue-related effects directly, using a model that included age-related performance changes over competitive career of track-and-field athletes. By building on these two studies, the purpose of our study was to develop an analytical tool for tracking the progression of performance of individual triathletes over their competitive career. Specifically, we have combined the approach of Bullock et al. (5) to account for the large environmental factors in triathlon with that of Hollings et al. (13) to describe the age-related changes in performance. In addition, the analysis has provided benchmark guides for talent selection programs, using profiles of successful triathletes, and allowed prediction of future race performances.

METHODS

Data. Official times of international triathlon races from World Cup, European Championships, World Triathlon Series (named previously World Championship Series), World Championships (including junior and under-23), and Olympic Games were downloaded from triathlon.org. Race dates were obtained also from triathlon.org. We searched the Internet for each athlete's date of birth, using infostradasports.com as a primary source. Athletes were excluded when date of birth was not found (150 male and 250 female athletes, mainly competing during the early 2000s and with a low number of performances), and performances were not included when athletes were disqualified or did not finish. Overall, 446 international competitions (224 men's and 222 women's) were raced during the period 2000–2012, with a total of 427 male and 337 female athletes competing in at least two of those competitions. Athletes were categorized as top athletes if they finished 16th or better at any World Championship or Olympic Games between 2008 and 2012. This classification was used to create performance benchmarks. For the purpose of developing career trajectories, these athletes were further separated into top 3 (10 males and 15 females), having ever finished 1st–3rd, and top 16 (43 males and 38 females), best finish of 4th–16th. The remaining athletes were grouped as others.

Career trajectories. Individual performance trajectories were generated using the high-performance mixed linear model procedure (Proc Hpmixed) in the Statistical Analysis System (Version 9.3, SAS Institute, Cary, NC). The fixed model included a mean quadratic trend for age, a linear trend for calendar year, and a factor to adjust sprint-distance into Olympic-distance times; all of these factors were interacted with athlete grouping factor with three levels (top 3, top 16, and others). Random effects were included to derive individual age quadratic trends and year adjustments for each athlete, the latter representing consistent deviation from the quadratic fitting in a particular year (due to injury, new training, etc.). A random effect for race accounted for environmental and other course-related factors (e.g., varying weather and water conditions, course distances, profiles of cycle, and run courses) on performance times. An unstructured covariance matrix was specified for the random effects representing the individual quadratic trajectories to allow for correlation between the three parameters defining the trajectories. The residual random effect, representing race-to-race athlete variability, was specified differently according to the type of competition (three levels: Elite World Championships, Olympic Games, and World Triathlon Series; World Cup, European Championships, and U23 World Championships; and Junior World Championships). This model was applied to each race stage (swim, cycle, run, and total time) and to each sex separately. Race times were log-transformed to yield the effects and errors in percent changes from the mean. Observations were considered outliers and excluded from the analysis if standardize residuals were greater than 4 SD from the predicted value; 54 swimming, 88 cycling, 80 running, and 63 total performances were thereby excluded from the analyses. The appropriateness of the model was investigated by analysis of residuals: plots for residuals versus predicted performances were inspected to ensure there was no unacceptable nonuniformity, and residuals were plotted against age (centered on age of peak performance) to ensure no substantial systematic trend in the residuals on either side of age of peak performance (the minimum of each quadratic curve). The quadratic model was deemed appropriate to represent performance changes with age.

Conversion of sprint to Olympic times. A conversion factor for adjusting sprint times to Olympic-distance times is implicit in the trajectories model as the difference between the two levels of the corresponding fixed effect. There were little differences between the conversion factors of the three groups (top 3, top 16, and others), so factors were averaged. To generate a conversion factor of the most use to the sport, we repeated the analysis excluding junior and under-23 performances, although the resulting conversion factor was very similar to that for all athletes.

Age of peak performance and age-related performance change. Athletes' age of peak performance was determined as the minimum of the individual quadratic age trend. For any individual trajectory that did not show the expected quadratic behavior, age of peak performance was not determined, and their values did not contribute to the mean. For the included athletes, age of their best placing at World Championships or Olympic Games (age of best performance) was also identified. Age-related performance change was calculated for each athlete as the performance change during the 5-yr period, leading to age of peak total performance. Age of peak performance and age-related performance change for swimming, cycling, running stages, and total performance are presented as means and SD. These statistics were compared, and magnitudes of standardized differences were assessed using thresholds of 0.2, 0.6, and 1.2 for small, moderate, and large, respectively (14). Uncertainty was calculated as 90% confidence limits.

Performance benchmark. A benchmark range for performance changes with age, representing the typical age-related performance changes among successful athletes, was obtained by combining the career trajectories of top athletes. The mean performance for each year of age was calculated using a meta-analytic model, where age estimates from individual athletes were combined using the inverse of the square of the standard error of the estimate as a weighting factor. The upper and lower limits of the benchmark range were calculated as the 90% reference range, assuming a normal distribution with mean (as just described) and SD given by the square root of the sum of the square of the standard error of estimated mean and the between-athlete variance, both provided by the meta-analytic model.

Prediction of race outcomes. Performances at 2012 London Olympic Games were predicted from the last race before the London Olympics (2012 Hamburg World Triathlon Series race). The mixed model for developing trajectories was modified by including venue as a predictor to characterize the effect of specific venues. Athletes' performances were predicted by extrapolating each athlete's quadratic trajectory to the dates of Olympic races and assuming the same conditions as in the 2011 London test event (which was held on a very similar race course and with a similar field of competition, as many countries used these performances for Olympic selection). We simulated 5000 individual races taking into account athletes' race-to-race variability as follows. In each race, each athlete's performance was given by the sum of their predicted value plus a random unit normal deviate multiplied by the standard error of the predicted value and an extra component, derived by randomly selecting from the residuals obtained with the original mixed model for trajectories. The chance of winning (the proportion of the 5000 races won by each athlete) and the ranking of the chances were then determined for athletes competing at the London Olympics. The predictability of performance was assessed by correlating the log-transformed rankings derived from the chance of winning with the log-transformed observed race placings. The performance of the female athlete Paula Findlay was not included as it was a clear outlier: she had been injured, was not physically fully prepared, and had not been competing internationally for more than a year (29). Correlations between log-transformed placings in Olympics and in each of 2012 World Triathlon Series races were also calculated and averaged using the Fisher transformation. The log transformation of placings was used to give equal importance to percent or factor differences in placings rather than absolute differences. For example, the difference between the second and the first is equivalent to the difference between the tenth and the fifth with log transformation and to the difference between the tenth and the ninth without transformation. Correlations were assessed using 0.1, 0.3, 0.5, 0.7, and 0.9 as thresholds for small, moderate, large, very large, and extremely large (14) and uncertainty expressed as 90% confidence limits. The predictability of race outcomes is affected by the variability of athletes' performances. Reliability analyses were performed for each calendar year for men and women to estimate typical differences between athletes and typical variation of athletes' total performance time from one race to the next. The typical differences between the athletes and the typical variation in men's and women's performances (expressed as SD) were used to explain differences in correlations.

RESULTS

Raw mean performance times (expressed as h:min:s) for sprint and Olympic distance races for both sexes are shown in Table 1. Variations between athletes within a race, representing the typical spread of performances in a race, are also displayed in Table 1.

Derived from the mixed model, mean times improved as a function of calendar year, at a rate of 0.25% (90% confidence limits = ±0.13%), 0.13% (±0.12%), and 0.09% (±0.12%) for men and 0.35% (±0.17%), 0.24% (±0.12%), and 0.15% (±0.12%) for women, for the top 3, top 16, and other athletes, respectively. The conversion factor for mean time between elite sprint and Olympic distance races was 1.99 (±0.04) for both sexes. In addition to the uncertainties shown in Table 1, athletes' performances varied from one race to the next typically by 1.5% of the race time for men and 1.5% of the race time for women (at high level races: World Triathlon Series, Elite World Championships, and Olympic Games). In swimming, cycling, and running, the variability values were 1.1%, 1.7%, and 3.2% for men and 1.5%, 1.7%, and 2.8% for women, respectively. The simple reliability analysis showed a similar 1.5% for the race-to-race variability for the 13-yr period, but in 2012, women had a larger variability (1.5) then men (1.2%). Uncertainties in these estimates of variability were negligible.

Figure 1 illustrates the difference between observed and corrected performances' times, after observed times being adjusted to a mean race. An athlete performance trajectory, displayed as the black curve, represents the fitting of a quadratic age trend to corrected times.

Figure 2 shows the performance trajectories as functions of age for top male and female athletes on the three stages individually and total race time. In Figure 2, top 3 athletes'

TABLE 1. Number of competitors (mean ± SD), race times (mean ± SD), and typical spread of performances in a race (mean of SD on the performance times in each race) in 224 men's and 222 women's sprint and Olympic distance triathlon races between 2000 and 2012.

	Men	Women
Sprint		
Competitors per race	60 ± 16	46 ± 13
Mean race time	0:59:31 ± 0:04:55	1:06:43 ± 0:05:36
SD of race time	0:02:43	0:03:04
Olympic		
Competitors per race	48 ± 13	35 ± 13
Mean race time	1:54:13 ± 0:05:03	2:07:01 ± 0:05:43
SD of race time	0:03:06	0:03:54

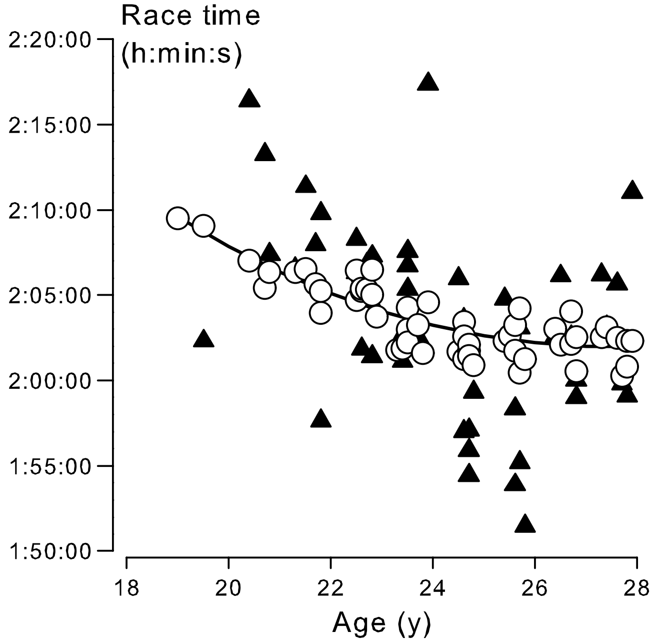

FIGURE 1—Observed (triangle) and corrected (circle) performances' times for an athlete, after times being adjusted to a mean race. The black curve is an athlete's trajectory, illustrating the fitting of a quadratic age trend to the corrected times.

performance trajectories are displayed in black while top 16 athletes' performances are presented in gray. Different patterns of progression were observed for swimming, cycling, running, and total performances and between sexes.

Performance trajectories were used to estimate age of peak performance and age-related performance change (Table 2). Differences between ages of peak performance for sexes and stages are trivial to moderate in magnitude, and most of the substantial differences are clear. There was a trivial difference between age of peak performance and age of best performance (age of best placing in a race; data not shown) at World Championship and/or Olympic Games. Age-related performance changes were evaluated during the 5-yr period leading to athletes' peak performance, with a negative change representing an improvement (decrease on performance times).

Top athletes' performances were then combined to produce a performance benchmark range, representing the typical pattern of performance changes with age. As it shown in Figure 3, an athlete's performance trajectory and year performance can then be assessed against the benchmark range.

The probabilities (chances) of winning the 2012 London Olympic Games were plotted against the observed race time at the Olympics (see Figure, Supplemental Digital Content, http://links.lww.com/MSS/A396. Relationship between observed performances in the 2012 London Olympics and predicted chances of winning; chances of winning were predicted using athletes' career trajectories derived including races up to the Olympics and assuming similar race conditions [environmental and race-course profile] as 2011 London test event). The correlations of Olympic placings with predictions using trajectories and with placings at the last race before the Olympics are shown in Figure 4. The mean correlations between Olympic placings and placings in each of the 2012 World Triathlon Series races before the Olympics are also shown. Predictions using trajectories produced the highest correlation for men, but for women, there was little difference between the three approaches.

DISCUSSION

In this study, we developed individual career trajectories of elite triathletes, investigating performance changes for the swim, cycle, and run race stages and total times. Performance change was modeled as a quadratic function of age and a linear function of calendar year in a mixed model that accounted for difference in mean race times arising from environmental and other course-related factors. By markedly reducing the scatter of race times, the model produced well-fitting individual quadratic trajectories that were suitable for assessment of athletes' performance changes during their competitive career.

Analysis of the residuals from the mixed model provided good evidence that the underlying quadratic function of age with clusters for race and athlete was appropriate for tracking athletes' performance changes for an age span of 15–41 yr. The other models used previously to describe individual performance changes in other sports would not have worked well with triathlon data. Alam et al. (1) modeled the performance of boys and girls in cross-country skiing as a sigmoid function of age to describe effects of puberty. Their analysis was limited to an age span of 10–18 yr and accounted for environmental factors by standardizing race times using the median of each race, which did not account properly for repeated measurement and athletes' abilities. For track-and-field athletics and swimming, Berthelot et al. (4) modeled athletes' annual best performances as a double exponential function of age by assuming performances from junior through elite ages improved exponentially to a plateau and then declined exponentially from elite through master ages. This complex nonlinear model was fitted to each athlete separately, so there was no correction for environmental and other race-related factors. Our model used race clusters to allow adjustment to an overall mean race time, thereby accounting for effect of environmental conditions and other race course–related factors that introduce extra variation in athletes' performances. The reduction of the scatter between observed and corrected performances is evident in Figure 1. Furthermore, our model included clusterings for athletes and athletes within year. The repeated measurements for athletes produced individual career trajectories, highlighting athletes' differences resulting from different physiology, training history, and nutrition regimes. The repeated measure for athletes within a year was included to identify consistent changes in performance arising for short-term (1-yr) changes in training programs, nutrition strategies, injuries, and so on.

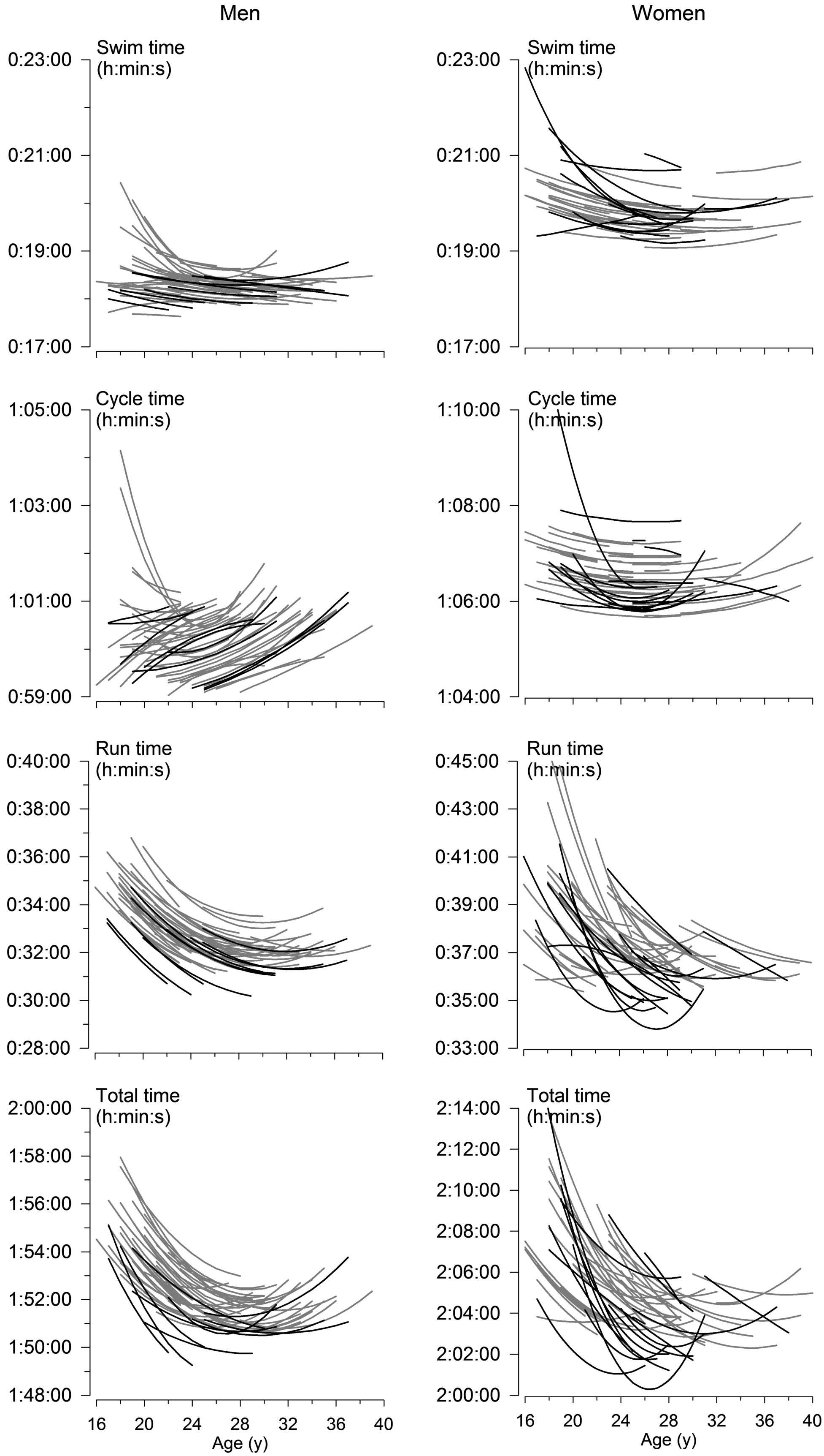

FIGURE 2—Performance trajectories as functions of age for top men and women for swimming, cycling, running, and total performance time. Top 3 athletes' trajectories are displayed in black, and top 16 are presented in gray (for athletes' classifications, see Methods section).

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TABLE 2. Predicted age of peak performance and 5-yr improvement for swim, bike, run, and total performance for the 'top' and all athletes (for athletes' classification, see Methods section). Only athletes who had already reached their predicted age of best performance were included in these estimates (30 for top men, 30 for top women, and 152 for other men and 79 for other women).

	Swim	Bike	Run	Total
Age of peak performance				
Top				
Men	25 ± 4	29 ± 3	28 ± 2	28 ± 2
Women	28 ± 2	28 ± 3	26 ± 5	27 ± 4
Other				
Men	26 ± 3	29 ± 2	29 ± 2	29 ± 2
Women	26 ± 5	28 ± 4	30 ± 3	28 ± 3
5-yr improvement to peak performance (%)				
Top				
Men	−0.8 ± 0.5	0.7 ± 0.3	−3.5 ± 1.1	−0.9 ± 0.3
Women	−1.1 ± 1.0	−0.2 ± 0.4	−5.1 ± 2.6	−1.9 ± 0.9
Other				
Men	−0.9 ± 0.5	0.5 ± 0.2	−2.1 ± 0.8	−0.7 ± 0.1
Women	−0.5 ± 0.8	0.0 ± 0.3	−2.4 ± 0.8	−0.7 ± 0.2

Data are presented as mean ± SD.
Uncertainties (90% confidence limits) for the means are ~0.3 SD for top men and women and ~0.15 SD for other men and ~0.2 SD for other women.

Career trajectories allow a direct and visually clear evaluation of athletes' performance changes (Fig. 2). For top men and women, performance changes for total time are closer to those for running than those for swimming and cycling. Running is also the triathlon stage where individual trajectories have the widest spread in time, indicating that differences among athletes in total performance arise mostly from differences in athletes' running performance. These findings are not unexpected, as running performance is the most important stage for success in triathlon (10,16,28).

Our career trajectories are consistent with the findings of Landers et al. (17), who compared junior and senior performance times in the 1997 World Championships and found the smallest percent difference for swim times and the biggest percent difference for run times. There are several explanations for the differences between trajectories for swimming, cycling, and running. Performance improvements within the athlete can result from physical and physiological maturation, training adaptation, improvement in skills and biomechanics, and increase in knowledge of race tactics (20,25,26). Differences in the development of physiology, biomechanics, and skill may explain the fact that running had the largest 5-yr improvement (Table 2), in particular, the improvement in economy arising from the increase in muscle and tendon stiffness with age and training (8,24). Triathletes are also likely to focus their training more on running (6), which would make improvement in aerobic power more evident in this stage. Furthermore, during the swim and cycle stages of a race, athletes must be strategic: they need a good position for the subsequent stage, but by drafting, they can reduce energy costs up to 30% (12) and thereby save energy for the running stage. Therefore, age-related changes in athletes' endurance abilities may not be manifested fully in the swimming and cycling trajectories. It should also be noted that most men's cycling trajectories show an increase in duration of the cycling stage with age. The most likely explanation for this effect is a gradual increase in difficulty of more recent cycling courses compared with those in the early 2000s (data not shown). The effect is not evident in women's cycling trajectories, presumably because the greater performance improvement for women (shown across all the stages, Table 2) offsets the slowing of cycling times. Furthermore, pack riding must reduce the effect of age on cycling performance time because the time of an individual athlete while riding in a pack will reflect the average of the performances of that pack. If there are smaller packs with women (27), there will a bigger effect of age on the women's trajectories.

Differences in performance changes for total time between top men and women are also evident in the results: men show a smaller spread of performances and trajectories of a similar shape (Fig. 2). This difference probably reflects a different developmental phase of the sport between the sexes. Men's uniformity presumably indicates a group of athletes who have been training since early ages as triathletes, who show similar levels of abilities for swimming and cycling, and for whom running is the most important stage for total performance. On other hand, the heterogeneity of women's trajectories for total time and their greater performance improvements reflect less depth in women's competitiveness. A similar phenomenon has occurred in other triathlon modalities (18), where bigger differences between winner and tenth-placed competitors have been reported for women compared with those for men (although women's differences have been decreasing faster than men's). The smaller depth of women's competitiveness results in a wider range in abilities, training, and physiology among athletes and therefore a wider variety of "ways" for women to succeed in triathlon.

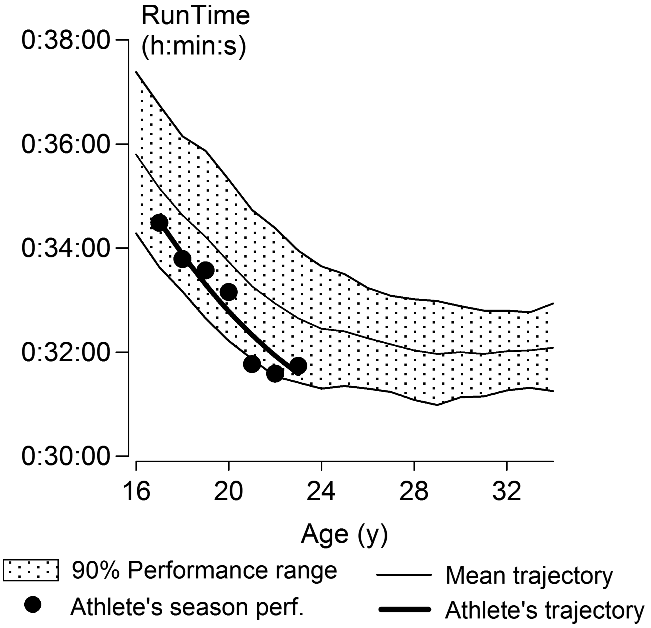

FIGURE 3—Comparison of an athlete's season performance and his trajectory against the typical age-related changes in running performance (mean and 90% performance range, see Methods section).

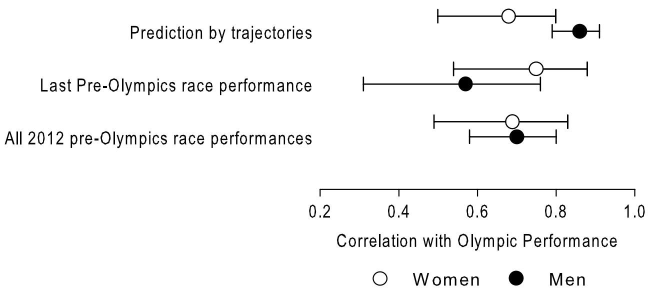

FIGURE 4—Correlations (with 90% confidence limits) of observed Olympic placings with predictions using trajectories and with placings at the last race before the Olympics. The mean correlation between Olympic placings and placings in each of the 2012 World Triathlon Series races before the Olympics is also shown.

Our study is not the first to address age-related changes in triathlon performance. Previous researchers have used cross-sectional studies with age-group athletes. Performances were deemed similar between ages 20 and 35 yr, and significant performance declines were reported after ages 40–55 yr, depending on race stage and triathlon distance (3,9,18,19). By developing a quadratic model to track performance progression of individuals within the period of their elite career, we have revealed performance differences across ages (Fig. 2) that were not evident in these cross-sectional studies.

Estimates of age of peak performance in triathlon were approximately 26–28 yr, with trivial to moderate differences between sexes and across stages. Our estimates of age of peak performance align well with age of athletes' best performance at a World Championships or Olympic Games. They were also consistent with previous findings for age of the best triathletes in an Olympic distance race: 27 ± 6 yr for men and 28 ± 6 yr for women (9). In longer distance triathlon, the age of best Ironman triathletes was 33–34 yr (11,23). Physiological characteristics are similar for Olympic and long-distance triathletes (21), so the difference between ages of peak performance is likely to be due to the fact that many triathletes compete in Ironman after retiring from Olympic competition, and that longer events may require more years of race experience.

Analyses of performance trajectories provide evidence of the typical pattern of progression of successful triathletes, which should assist with the setting of benchmarks for talent identification and development programs. The analysis of athletes' trajectories and their season performances ought also to help detect successful (and unsuccessful) performance improvement strategies. In Figure 3, we gave an example of these applications. The athlete shown is progressing within the successful range, and at age 21 yr, he improved his running performance substantially. A subsequent analysis of this athlete's training history may reveal whether a new training approach, coach, nutrition strategy, and so on, contributed to the performance improvement. Furthermore, the comparison of swim, cycle, and run trajectories of the same athlete against benchmarks will highlight the athlete's strongest and weakest stages, providing additional guidance for the athlete's career.

Career trajectories can also be used to predict performance. We found strong associations between observed and predicted performances at the 2012 London Olympic Games, although these associations were not much higher than those obtained with the simpler approach of correlating typical race placings at previous competition(s) with Olympic placings. In addition, the correlation using predictions was higher for the men than for the women. Analysis of the residuals for the 13-yr period showed that men and women have similar race-to-race variability, but the annual race-to-race reliability analysis showed that female triathletes in 2012 were more variable from one race to the next compared with males. This greater variability led to a lower predictability of women's outcomes and hence the lower correlations for women.

Practical applications for tracking triathletes' performances with our method could be developed further. First, tables showing annual percent improvements for each year of age, as means and SD, will make expected performance goals clear and easy to communicate to coaches and athletes. Second, career trajectories were developed giving equal importance to each performance; however, predictions for future performance might be more accurate if more weight is assigned to more recent performances. Third, performance predictions may also be improved by including random effects to specify individual responses to environmental and other course-related factors (e.g., temperature, wetsuit swim, and race-course profiles) and importance of the race (e.g., Olympic Games, World Triathlon Series, and World Cup races). Fourth, data were limited to international races performed at a professional level performances at younger ages in lower level competitions should be included in the analysis to make the method more useful for talent identification. For this purpose, data of substantial numbers of the same athletes competing at international and at lower level competitions would be needed. Finally, an athlete's season performance appearing as an unexpectedly large deviation from the quadratic trajectory could provide evidence of the use of a banned performance-enhancing substance.

CONCLUSIONS

We have presented a new method for tracking the development of elite triathletes performing internationally. The resulting career trajectories and reference ranges represent objective measures of performance that should provide useful information for funding talented athletes and identifying successful (or unsuccessful) performance enhancement strategies. Furthermore, the comparison of an athlete's three trajectories (swim, cycle, and run) with corresponding reference ranges should also help apportion training to the specific race stages. The full use of the method presented here to address relative strength and weakness of a given athlete in the different race stages will need consideration of contribution of each stage to total time. Trajectories also offer a small advantage over usual race placings for predicting men's performance, but further refinements of the model, by including athletes' individual responses to race conditions, may allow more accurate projection of triathletes' trajectories into the future.

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The authors have no conflicts of interest to declare.

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REFERENCES

1. Alam M, Carling K, Chen R, Liang Y. How to determine the progression of young skiers? *Chance*. 2008;21:13–9.
2. Allen SV, Hopkins WG, Vandenbogaerde TJ. Career performance trajectories of Olympic swimmers. In: *17th Annual Congress of the European College Sport Science*, 2012 Jul 4–7: Bruges (Belgium). Vrije Universiteit Brussel and Université Libre de Bruxelles; 2012. 191 p.
3. Bernard T, Sultana F, Lepers R, Hausswirth C, Brisswalter J. Age-related decline in Olympic triathlon performance: effect of locomotion mode. *Exp Aging Res*. 2010;36:64–78.
4. Berthelot G, Len S, Hellard P, et al. Exponential growth combined with exponential decline explains lifetime performance evolution in individual and human species. *Age*. 2012;34:1001–9.
5. Bullock N, Hopkins WG. Methods for tracking athletes' competitive performance in skeleton. *J Sports Sci*. 2009;27:937–40.
6. Bürgi A. Career Development of World Class Triathletes. In *ITU Science and Triathlon World Conference, 2013*: Lausanne; 2013.
7. Chatard JC, Senegas X, Selles M, Dreanot P, Geyssant A. Wetsuit effect: a comparison between competitive swimmers and triathletes. *Med Sci Sports Exerc*. 1995;27(4):580–6.
8. Dumke CL, Pfaffenroth CM, McBride JM, McCauley GO. Relationship between muscle strength, power and stiffness and running economy in trained male runners. *Int J Sports Physiol Perform*. 2010;5:249–61.
9. Etter F, Knechtle B, Bukowski A, Rüst CA, Rosemann T, Lepers R. Age and gender interactions in short distance triathlon performance. *J Sports Sci*. 2013;31:996–1006.
10. Fröhlich M, Klein M, Pieter A, Emrich E, Gießing J. Consequences of the three disciplines on the overall result in olympic-distance triathlon. *Int J Sports Sci Eng*. 2008;2:204–10.
11. Gallmann D, Knechtle B, Rüst CA, Rosemann T, Lepers R. Elite triathletes in 'Ironman Hawaii'get older but faster. *Age*. 2013; 36:1–10.
12. Hausswirth C, Brisswalter J. Strategies for improving performance in long duration events: Olympic distance triathlon. *Sports Med*. 2008;38:881–91.
13. Hollings SC, Hopkins WG, Hume PA. Environmental and venue-related factors affecting the performance of elite male track athletes. *Eur J Sport Sci*. 2012;12:201–6.
14. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*. 2009;41(1):3–12.
15. *ITU Competition Rules*. 2013. International Triathlon Union.
16. Knechtle B, Kohler G. Running performance, not anthropometric factors, is associated with race success in a Triple Iron Triathlon. *Br J Sports Med*. 2009;43:437–41.
17. Landers G, Blanksby B, Ackland T, Smith D. Morphology and performance of world championship triathletes. *Ann Hum Biol*. 2000;27:387–400.
18. Lepers R, Knechtle B, Stapley PJ. Trends in triathlon performance: effects of sex and age. *Sports Med*. 2013;43:1–13.
19. Lepers R, Sultana F, Bernard T, Hausswirth C, Brisswalter J. Age-related changes in triathlon performances. *Int J Sports Med*. 2009;31: 251–6.
20. Mikulic P. Maturation to elite status: a six-year physiological case study of a world champion rowing crew. *Eur J Appl Physiol*. 2011; 111:2363–8.
21. Millet GP, Dréano P, Bentley DJ. Physiological characteristics of elite short-and long-distance triathletes. *Eur J Appl Physiol*. 2003; 88:427–30.
22. Pike J, Hopkins WG, Nottle C. Overall trends and individual trajectories of swimming performances in a decade of New Zealand national championships. In: *XIth International Symposium on Biomechanics and Medicine in Swimming*; 2010 Jun 16–19: Oslo (Norway); 2010. p. 72.
23. Rüst CA, Knechtle B, Knechtle P, Rosemann T, Lepers R. Age of peak performance in elite male and female Ironman triathletes competing in Ironman Switzerland, a qualifier for the Ironman World Championship, Ironman Hawaii, from 1995 to 2011. *Open Access J Sports Med*. 2012;3:175–82.
24. Saunders PU, Pyne DB, Telford RD, Hawley JA. Factors affecting running economy in trained distance runners. *Sports Med*. 2004; 34:465–85.
25. Sowell CB, Mounts WS Jr. Ability, age, and performance conclusions from the Ironman Triathlon World Championship. *J Sports Econ*. 2005;6:78–97.
26. Stevenson J, Song H, Cooper JA. Age and sex differences pertaining to modes of locomotion in triathlon. *Med Sci Sports Exerc*. 2013;45(5):976–84.
27. Vleck VE, Bentley DJ, Millet GP, Bürgi A. Pacing during an elite Olympic distance triathlon: comparison between male and female competitors. *J Sci Med Sport*. 2008;11:424–32.
28. Vleck VE, Bürgi A, Bently DJ. The consequences of swim, cycle, and run performance on overall result in elite olympic distance triathlon. *Int J Sports Med*. 2006;27:43–8.
29. Yahoo! Sports Canada [Internet]. Paula Findlay breaks down, apologizes after Olympic women's triathlon; [cited 2013 Jan 29]. Available from: http://ca.sports.yahoo.com/blogs/eh-game/paula-findlay-breaks-down-apologizes-olympic-women-triathlon-144038613.html.
30. Young B, Starkes J. Career-span analyses of track performance: longitudinal data present a more optimistic view of age-related performance decline. *Exp Aging Res*. 2005;31:69–90.