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Gorzi, Ali, Khantan, Mina, Khademnoe, Omid & Eston, Roger 2021 'Prediction of elite athletes' performance by analysis of peak-performance age and age-related performance progression', *European Journal of Sport Science*, online, pp. 1-22

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European Journal of Sport Science

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tejs20

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To cite this article: Ali Gorzi , Mina Khantan , Omid Khademnoe & Roger Eston (2021): Prediction of elite athletes' performance by analysis of peak-performance age and age-related performance progression, European Journal of Sport Science, DOI: 10.1080/17461391.2020.1867240

To link to this article: https://doi.org/10.1080/17461391.2020.1867240

Accepted author version posted online: 04 Jan 2021.

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Publisher: Taylor & Francis & European College of Sport Science

Journal: *European Journal of Sport Science*

DOI: 10.1080/17461391.2020.1867240

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Prediction of elite athletes' performance by analysis of peak-performance age and age-related performance progression

Running head: **An Analysis for Prediction of Athletes' Performance**

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Conflict of Interest Statement: The authors report no conflict of interest.

Author Contribution: AG and MK: research concept and study design, literature review, data collection, data analysis and interpretation; AG: writing of the manuscript; OK: statistical analyses, writing of the manuscript; RE: literature review and reviewing and editing a draft of the manuscript.

Figure/Table: 2 figures and 2 Tables.

Word count: 4119

References numbers: 41

Acknowledgment: We thank Farideh Ghasemi, Neda ahmadpour, Samaneh Khaleghi and Fatemeh Khatami (University of Zanjan) for helping us in providing data.

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Abstract

The aim of this study was to analyse age-related performance progression and peak-performance age (PPA) in elite track and field athletes and to use a model to predict peak performance. Best performances of world-class athletes from ages 14-15 y up to and including the last Olympic year (n=798), all-time top lists (n= 444), and world record-holders (n=43) were considered in all 22 disciplines for men and 21 disciplines for women. A discipline/sex-specified model was used by applying dynamic panel data methods to analyze the performance trends. Profile analysis showed that PPA of all-time top list throwers was higher than middle-distance runners ($P<0.001$), distance runners ($P<0.05$), and jumpers ($P<0.05$) in men and higher ($P<0.05$) than middle-distance runners in women. Olympic year top list athletes showed that PPA of women throwers was higher than sprinters ($P<0.001$) and middle-distance runners ($P<0.05$), and PPA of women distance runners was higher ($P<0.05$) than sprinters. In both all-time ($P<0.05$) and Olympic year ($P<0.05$) top lists, the PPA of men race walkers was higher than middle-distance runners. Performance over the preceding 1-2 years (in all disciplines), height (in Long Jump Men; Long Jump Women; Triple Jump Men) and weight (in Discus Throwing Men) indices, respectively, are important ($P<0.05$) for predicting future records with different coefficients in different disciplines. The models provide a useful tool for coaches to predict peak performance records and PPA of their athletes which may be of benefit with goal-setting and evaluation of performance progression at different ages in track and field athletics.

Keywords: Conditioning, Goal-setting, Track & field, Sex Differences, Prediction of Records.

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INTRODUCTION

Growth and development are accompanied by numerous physiological changes which affect physical performance. Development of skeletal muscles, bones, nervous, cardiovascular, hormonal, cardiorespiratory and other systems and organs, enhanced by exercise training, enable athletes to improve performance (4). On the other hand, aging, as an inevitable process of growth, challenges the physiological capacities and performance of athletes.

Track and field sports demand event-specific abilities (38), which are largely dependent on relationships between speed, endurance, strength and power, all of which are related to maturation and age. Strength increases with puberty and remains almost constant until the age of 40 (20, 30), but other performance indices like speed and power decrease at an earlier age (3, 31, 36). The duration of the 'window' for peak performance is similar in men

and women, although peak performance ages (PPA) are different for specific sports (13, 33). For example, the window of peak performance for male sprinters (3.7-4.6 y) and hurdlers (3.5-3.6 y) is shorter than for other event groups (4.9-6.1 y) in men (13).

Peak performance in running and jumping events are almost equal in boys and girls until the age of 12 y, after which there are greater increases in strength and power in boys (22, 38). In general, sex differences in peak performance range between 10-12% for running events and 19% for jumping events (6, 29, 32, 37). Differences beyond this age have been attributed to hormone-dependent and red blood cell mass changes in physiological properties (10, 28).

In a study involving Olympic Games or a World Athletics Championships during 2000 and 2009 in 19 disciplines, Holling et al. (2014) observed substantial inter-event group and sex differences in the PPA of professional runners and throwers (13). The PPA was higher in throwers compared to runners and jumpers. Also, compared with men, PPA was higher in running and lower for throwing events in women (13).

Beyond sex differences, knowledge of how age impacts on peak performance, and when performance starts to decline in various events of track and field, and comparison of all-time and todays athletes is of interest. Longitudinal data from top athletes' records at different ages could provide essential information to create an analysis for predicting the performance of developing athletes in subsequent years (18, 34, 39). Understanding the relationships between height, weight, body mass index, PPA, and trend of improvement in different events may be useful to assist in talent identification, specialization age, goal-setting, planning, injury prevention, and evaluating performance progression. Therefore, the aim of the present study was to analyse age-related performance progression and PPA in elite track and field athletes and to use a model to predict peak performance.

METHODS

Data sample

The longitudinal data used in this study comprised season-best performances up to the most recent Olympic year (season 2015-2016) for 798 top list athletes from 85 countries (427 Men; 371 Women; N=11-35 data available in different events) from the IAAF Annual Report-2016 (23). Considering the competition of some athletes in two or three events (e.g., 100m, 200m, and 400m), 985 data were obtained for the Olympic year. The data also included all-time top 10 list performances in track and field events which included 444 athletes (226 M: 218 W). We also included world record-holder performances (n=43) from the world athletics website (16), up to March 2020 or

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until retiring. Since all data are publicly available (https://www.worldathletics.org/Stats Zone) (16), no permission or informed consent were deemed necessary for this study.

Chronological age was calculated as competition year minus date of birth (DOB). Since pilot analysis showed no significant differences between groups (equal distribution), the upper and lower limit of the age (month of DOB and the month of competitions) were not considered. We used the 2015-2016 Olympic year information since this period is vital for all top athletes to have the best performance to qualify for the Olympic Games.

All data were classified into eight major groups of events: the 22 official Olympic disciplines for men and the 21 disciplines for women (**1**- *Sprints*: 100m, 200m, 400m; **2**- *Hurdles*: 110mH (M)/100mH (W), 400mH; **3**- *Middle-Distance*: 800m, 1500m; **4**- *Distance*: 3000m Steeplechase-SC, 5000m, 10000m, 42.195km- Marathon; **5**- *Race Walking*-RW: 20km, 50km RW (M); **6**- *Jumps*: Long Jumps-LJ, Triple Jump-TJ, Height Jump-HJ, Pole Vault-PV; **7**- *Throws*: Shot Put-SP, Discus Throw-DT, Javelin Throw-JT, Hammer Throw-HT; and **8**- *Combined*: Decathlon-Dec (M), Heptathlon-Hep (W). The 50km RW discipline was added for women recently (2017), but we have not included it in this study. Indoor competition results of comparable events (i.e., LJ, TJ, HJ, PV, SP) were included. All official rules and regulations were taken into account. The records are restricted to the individual best performance (season-best) for each event during the cited years. Records in sprints, hurdles and 800m were considered in centesimal, and for 1500m, long distance and RW records, only seconds were considered. For example, for the 800m a time of 1′.43′′.89 was noted as 103.89 s. For the 10000m a time of 32′.52′′ was noted as 32.86 min (Table 2). At least 2 data available for each younger age group in each discipline (e.g. 12 y in W HJ and W PV …, - 20 y in M 50 km RW) and 2 data available in the senior age groups (e.g. 31 y in W 1500m …, - 40 y in M DT) were also considered (Table 2). For each athlete, the available data from 12 years old up to March 2020 or retirement age were considered, but outlier data from each age group were excluded by Boxplot.

Despite different competition regulation standards across age categories (i.e., weight of throwing implements, hurdle height, etc.), the throwing and hurdle results were included. Men and women use different implement weights in throws (Shot put: 7.260 kg vs. 4.00 kg; Hammer throw: 7.260 kg vs. 4.00 kg; Discus throw: 2.00 kg vs. 1.00 kg; Javelin throw: 0.80 kg vs. 0.60 kg) (40).

For height: a) it was not possible to access 5% of the data for the all-time top lists, and b) there was more than a 30% overlap (the same athletes in two groups) data. However, we analysed and reported significant differences between these data (Olympic-year with All-time). In total, there was an approximately 30% overlap between All-time athletes within Olympic year lists (31% in men and 28% in women); *Men* (sprints: 5%3, hurdles: 30%, mid-distance: 45%, distance: 35%, race walking:15%, Jumps: 27%, throws: 19%, combined:40%); *Women* (sprints:

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30%, hurdles: 35%, mid-distance: 15%, distance: 42%, race walking: 30%, jumps: 27%, throws: 15%, combined: 30%). There was %13% overlap for the Olympic year (133/985) with All-time data.

We used mixed data for Olympic year and all-time data for analysis because: a) predicted records based on only All-time results had more error for current athletes; b)- doping control for Olympic year athletes and training quality are improved; c) we were unable to access 5% of height and weight data from All-time lists; and d) pilot analysis showed more precise results in mixed version.

Statistical analyses

Descriptive statistics are presented as means and standard deviations of height, weight, BMI, PPA in the Olympic year and All-Time top lists and annual records of all athletes at different ages. Trend curves of improvement in performances in all disciplines for men and women were presented. Using these peak performance trends (Table 2), a discipline/sex-specified analysis was used by applying unbalanced dynamic panel data methods to analyze the collected data, and also plm package (linear models for panel data) in R program (version 3.6.2) to estimate parameters of the analysis. Overlapping data (the same data in Olympic year and all-time top lists) were excluded for analysis.

If the same individuals in a cross-sectional sample are observed repeatedly two or more times, the obtained observations are represented as formatting a panel or longitudinal data set. In fact, panel data analysis includes a combination of regression (cross-sectional) and time series. When there are n athletes and we have everyone's records in T time periods, we will have nT observations. Regression analysis, in which the relationships between dependent variables and independent variables are studied, is a special type of panel data, when T=1 (single point of time). In contrast, time series data, in which the trend of one or more variables over time is analyzed, is a type of panel data with n=1. In the natural sciences panel data analysis is known as longitudinal data analysis. If for any individual there exists an observation for every time period, this is categorized as balanced panel data, and if some observations are missing, this is categorized as unbalanced panel data. By combining the regression analysis and time series, panel data has advantages over both of them. More details about this subject can be found in Hsiao (2005) (14).Comprehensive studies and explanations of panel data analysis methods are described by Hsiao (2003) (15), Frees (2004) (8), Arellano (2003) (2) and Nerlove (2002) (25).

The normality of data analyzed by K-S and outlier data (worst in annual records but not in PPA) were excluded by Boxplot. One Way Analysis of Variance (ANOVA) followed by Tukey's post hoc test were used for comparison of height and PPA among 8 event groups. Independent T-tests were used for comparison of the height and PPA between men and women and between All-Time lists and Olympic year in 8 event groups and 22/21 disciplines. Cohen's d effect size (ES) was analysed for ANOVA and T-test comparisons.

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RESULTS

Profile analysis of Height for Olympic year top lists

Analysis of Olympic year top lists for men ($F_{7,491}$=76.56, P<0.001, ES=0.522) showed that height of sprinters, hurdlers, jumpers, throwers, and decathlon athletes was greater compared to middle-distance (all were P<0.001), distance runners (P<0.001) and race walkers (P<0.001). Throwers' height was greater compared to sprinters (P<0.001), hurdlers (P<0.05) and jumpers (P<0.001). (Figure 1). Discus throwers were the tallest (1.92 ± 0.07 m) and 42 km (marathon) runners were the smallest in stature (1.70 ± 0.06 m). Similar results were observed for height of all-time athletes.

Analysis of Olympic year top lists for women ($F_{7,469}$=58.35, P<0.001, ES=0.466) showed that the height of throwers, jumpers and heptathlon athletes was greater than for sprinters (P<0.001), hurdlers (P<0.001; P<0.001; P<0.05), middle-distance runners (P<0.001), distance runners (P<0.001) and race walkers (P<0.001) (Figure 1). Discus and high jump athletes were the tallest (1.84±0.06 m; 1.84±0.05 m, respectively) and 5000m, 10000m and 42 km runners were the smallest (1.63±0.06 m; 1.62±0.06 m; 1.62±0.05 m). Similar results were observed for all-time athletes' height.

There was no significant difference between the height of all-time and Olympic year top list results in the 8 main event groups (Figure 1). However, the height of all-time top lists in both men (1.84±0.09 m) and women (1.72±0.08 m) was greater (2 cm and 1.4 cm, respectively) than the height of Olympic year men (1.82±0.09 m) and women (1.70±0.08 m).

Fig 1.

Profile analysis of PPA

For men, the Olympic year top lists data ($F_{7,495}$=2.65, P<0.05, ES=0.036) showed that PPA of race walkers was higher (P<0.05) compared to middle-distance runners. For women ($F_{7,474}$=3.94, P<0.001, ES=0.055), PPA was higher for throwers compared to sprinters (P<0.001) and middle-distance runners (P<0.05). PPA for distance runners was higher (P<0.05) than for sprinters and but not significantly higher (P=0.083) than middle-distance runners (Figure 2). All-time top 10 data showed that PPA of men ($F_{7,217}$=3.99, P<0.001, ES=0.114) throwers was higher than middle-distance runners (P<0.001), distance runners (P<0.05), and jumpers (P<0.05). The PPA of race walkers was also significantly (P<0.05) higher than middle-distance runners. For women ($F_{7,210}$=2.72, P<0.05, ES=0.083), PPA of throwers was significantly higher (P<0.05) than middle-distance runners. (Figure 2).

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Fig 2.

Olympic year top list male athletes ($F_{21,481}$=2.23, <0.05, ES=0.089) showed that PPA in 42 km runners and 50 km race walkers was higher than 800 m (P<0.05; P<0.001) and 5000 m (P<0.05) runners. The 50 km race walkers also had a higher PPA (P<0.05) compared to 10000 m runners. The 50 km race walkers had the highest PPA (28±4.58 y), and 800 m runners had the lowest (22.90±3.33 y). For women ($F_{20,461}$=3.28, P<0.001, ES=0.125), PPA of 42 km runners, was higher than 1500 m (P<0.001) and 5000m (P<0.05) runners. The 42 km runners had the highest PPA (27.80±3.85 y), and 1500 m runners had the lowest PPA (23.61±3.22 y).

The PPA for all-time top 10 for men ($F_{21,203}$=4.23, P<0.001, ES=0.305) was higher for 42 km runners and 50 km race walkers compared to 800m (P<0.001), 5000m (P<0.001), and 10000m runners (P<0.05). The higher PPA for 50 km race walkers compared to 20 km race walkers was not statistically significant (P=0.084). The 50 km race walkers had the highest PPA (30.1±5.85 y), and 5000m runners the lowest PPA (21.4±2.17 y). For women ($F_{20,197}$=2.23, P<0.05, ES=0.185), the PPA of 42 km distance runners was higher (P<0.05) than 1500 m runners. Javelin throwers (29.2±4.54 y) had the highest PPA, and 1500 m runners (21.9±3.87 y) had the lowest PPA.

Analysis of Olympic year top lists, showed that PPA in women distance runners was higher ($F_{1,240}$=4.75, P<0.05, ES=0.019) than men. The PPA of women 800m ($F_{1,41}$=5.12, P<0.05, ES=0.111), javelin throwers ($F_{1,32}$=4.81, P<0.05, ES=0.131) and triple jumpers ($F_{1,33}$=5.75, P<0.05, ES=0.149) was higher compared to men, and not statistically significant for 10000 m runners (P=0.073). On the other hand, the all-time top 10 lists showed that the PPA of men decathlon athletes was higher ($F_{1,18}$=7.96, P<0.05, ES=0.30) than women heptathlon athletes. Also, the PPA of men 1500 m runners was higher ($F_{1,18}$=5.49, P<0.05, ES=0.234) compared to women. Conversely, the PPA of women 800 m runners ($F_{1,18}$=7.03, P<0.05, ES=0.281), 5000m runners ($F_{1,18}$=9.72, P<0.05, ES=0.351) and high jumpers ($F_{1,25}$=4.34, P<0.05, ES=0.148) was higher than their male counterparts.

The difference in records between men and women at PPA for Olympic year were about 10 -12% in sprints and hurdles, 12-15% in middle-distance, distance and RW, 19-23% in jumps and 2-10% in the shot put, discus and hammer thrower, and 37% in javelin throwers.

PPA of all-time men throwers was higher ($F_{1,104}$=18.28, P<0.001, ES=0.150) than Olympic year throwers. Specifically, the PPA of all-time men shot putters ($F_{1,30}$=7.99, P<0.05, ES=0.210) and hammer throwers ($F_{1,19}$=4.78, P<0.05, ES=0.201) was higher. Also, for women, the PPA of all-time jumper ($F_{1,139}$=7.87, P<0.05, ES=0.054) and shot putters ($F_{1,23}$=5.57, P<0.05, ES=0.195) were higher than Olympic year counterparts.

Performance progression

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The analysis introduced by dynamic panel data to predict the records at different ages for all men and women disciplines are presented in Table 1. Our analysis showed that performance over the preceding 1-2 years (in all disciplines), height (in Long Jump Men; Long Jump Women; Triple Jump Men) and weight (in Discus Throwing Men) indices, respectively, are important ($P<0.05$) for predicting future records with different coefficients in different disciplines. Other indices like BMI, 3 years ago records or weight and height (in some other disciplines) were not significantly important in the prediction of future records ($P>0.05$). It should be noted that for the prediction of future records by these models, the following need to be taken into consideration: Height and weight should be within the normal range of specific disciplines; prediction of performance is valid within the normal range of PPA for specific disciplines.

Table 1.

Key to abbreviations in Table 1.Where The R_t is predicted record at a certain age, R_{t-1} is the best personal record one year ago, R_{t-2} is the best personal record two years ago, Rt.m is the average (mean) records of mixed Olympic year and All-time top lists records at certain age (Table 2), H is the adulthood height of the athlete and W is the adulthood weight of the athlete. For example; future performances for a 18 year old 400m runner up to 23 years of age, with 1.82 m height, and best performances of 47.70 and 46.90 s at the ages of 16 and 17, respectively, are estimated to be 46.01, 45.96, 45.22, 44.72, 44.54, and 44.43s at 18, 19, 20, 21, 22 and 23 years of age, respectively.

Table 2.

DISCUSSION

Our results showed that PPA of all-time top lists throwers was higher than middle-distance runners, distance runners, and jumpers in men, and higher than middle-distance runners in women. Olympic year top list athletes showed that PPA of women throwers was higher than sprinters and middle-distance runners, and PPA of women distance runners was higher than sprinters. In both all-time and Olympic year top lists, the PPA for men race walkers was higher than middle-distance runners. These results are consistent with a previous study which reported higher PPA for throwers and distance runners (12). Race walking and decathlon/heptathlon were not considered in their study. Hulme et al. (2017) suggested that lower PPA in middle-distance runners could be related to the higher injury rate due to the inherent bounding generated during the training process in these events (17). Therefore, coaches of sprinters and middle-distance runners need to be cognisant that they have a limited window of time for achieving best performances, which is limited by the extent to which the athlete remains free of injury. Changing discipline with aging could be an appropriate strategy (12), especially from sprint and middle-distance to long-

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distance or race-walking events, and from distance running to longer distance running (26). Sprinters and middle-distance runners may have a greater propensity to convert to another athletic event. For example, all-time PPA for 5000m, 10000m and 42 km were 21, 23 and 29 y, respectively for men, and 24, 26, 28 y for women.

It seems that in PPA differences between event groups of all-time athletes are greater in men. Conversely, differences in PPA between event groups in Olympic year athletes, are greater in women. Aging is reported to lead to a decrease in ability to perform maximal and rapid contractions, particularly in men (19, 41). Taken together, these findings demonstrate that responsiveness time to the training of strength is longer than for other factors like speed, power, and endurance. Throwers, race walkers and distance runners reach their best performances at an older age than other event groups (sprinters, hurdlers, middle-distance runners, jumpers and combined athletes). These observations are important with regard to the expectations of the time it takes to attain peak performance. Therefore, these athletes and their coaches should have realistic expectations of the longer time to reach PPA, with the knowledge that later progression and best performance are normally achieved at a higher PPA for throwers, race walkers and distance runners. Earlier reduction in the number and size of type II muscle fibers (9) is one of the biological reasons for these differences. Also, previous studies reported that peak performance in hand-grip strength occurs between the ages of 30-39 years in men and women, and is dependent on quality and girth of muscle (1). Another reason for higher PPA of throwers in comparison with other lower body-dependent disciplines, is that legs experience maximum growth before the trunk, hands, neck and head (21), and therefore, running and jumping events are characterized with an earlier PPA than throwers. The greater training volume (training years) needed to attain a desired running economy for distance running (24) is a probable factor in late PPA of distance runners.

The higher PPA for throwers (men) and jumpers (women) in comparison to other event groups could be related to the number of years duration of training needed to attain the required muscle mass for maximal strength, and time needed to gain mastery of complex, technique-based field disciplines compared to more fundamental skills like running (12).

The PPA of women all-time and Olympic year top-list athletes in 800 m, 5000 m and 10000 m runners, high jump, triple jump and javelin were higher than men counterparts. Also, women world record-holders in 11 disciplines were older than men at PPA, and only six men world record-holders were older than women counterparts at PPA. Also, only PPA in men decathlon athletes of all-time top 10 lists was significantly higher than women heptathlon athletes. It seems that socio-cultural factors, childbearing, late start of professional training, as well as sex differences are important factors in peak performance latency in women (12).

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In considering the weight differences of throwing implements for men and women events (40), the later PPA of women javelin throwers may be attributed to the greater relative implement weight differences for men and women in this discipline (e.g., Shot put: 7.260 kg vs. 4.00 kg = 55%; Javelin: 0.8 kg v 0.6 kg = 75%). Adult women have about 50% (upper body) to 60% (lower body) strength of men (20% difference in powerful athletes with similar body mass) (5, 35). The javelin throw is critically dependent on upper body strength and power. The higher difference in javelin throw performance between men and women at PPA is 37%, compared to a 2-10% difference in all other throws, provides some support for this rationale.

As shown in Figure 2, Olympic year top list PPA were lower than all-time top 10 in most event groups of men and women (Olympic year; M: 24.86±3.66; W: 25.19±3.57; All-time; M: 26.04±3.91; W: 26.18±3.79). Also, PPA of record-holders is not necessarily equal to average PPA of Olympic year top lists or all-time top 10 list athletes. It seems that today's athletes (Olympic year) have more competition opportunities compared with the all-time top 10 athletes and this may result in early PPA (11). Also, compared with all-time athletes, today's athletes start specific training earlier based on the concept of the certain training volume (training years until peak performance) needed to reach a high level of running economy, especially in distance running (24), and reach peak performance at younger ages. Training years required to improve running economy likely explains the observed trends towards higher PPA with increasing long-distance duration. This early PPA in Olympic year top list concurs with the findings of Noble et al. (2017) who reported lower PPA and retiring ages of African marathon runners in comparison with non-African marathon runners, possibly due to earlier ages of specialized training (27).

Interestingly, our results showed that most athletes with an earlier PPA have a short athletics career. For example, about 80% of men and women Olympic year sprinters, 110m hurdlers, 10000m runners, all jumpers, hammer throwers, shot putters, and heptathlon athletes who reached their PPA at 19-21 years of age, retired before the age of 22. Dick (2013) reported that only 9% of world junior competition medalists between 2000 - 2010 translated to the finalists in London 2012 Olympic Games (7). This "athlete dropout" may be attributable to the early specialization. Available data from elite athletes progression in this study (Table 2) show that sprinters, jumpers and middle-distance runner started specialization at 12-15 y but throwers, hurdlers, race walkers and distance runners started specialization at 15-20 y. Also, based on world record-holders and all-time top 10 list data, runners who participated in more than a single discipline, have better records than athletes who participated in only one discipline. It seems that multidiscipline athletes improve all-around development more than other athletes.

Profile analysis of athletes showed that there was no significant difference between the height of Olympic year and all-time athletes, although the height of all-time men and women top lists were 3 cm and 1.4 cm higher than Olympic year athletes. Since all-time top list records are better than Olympic year athletes' records, it seems that height is a critical factor in athletics performance of some disciplines. Inclusion of height in the performance

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prediction analysis of Long Jump Men; Long Jump Women; Triple Jump Men by dynamic panel data, support this idea. Although, in Olympic Games athletes generally focus on winning the medal, rather than the setting better records. Prediction of the standard height for a specific discipline at PPA is accessible in norms of height growth WHO standards for boys and girls.

PRACTICAL APPLICATIONS: We have analyzed PPA and age-related performance progression in elite athletes of different discipline and used a discipline/sex-specified analysis for predicting records. Based on our results, sprinters and middle-distance runners have fewer years to setting best performances, but throwers, race walkers and distance runners should not be disappointed with late progression. Based on our analysis, the last 1-2 years' records, and, in some disciplines, respective height and weight indices are important in predicting future records with different coefficients in different disciplines. These data may help with goal setting, monitoring and evaluating performance progression. For the prediction of future records by this model, the following need to be taken into consideration: height and weight should be within the normal range of specific disciplines, and prediction of records are valid until the normal range of PPA for specific disciplines. However, since peak performance is influenced by training, nutritional, mental, environmental and sometimes pharmaceutical interventions, the model applied in this study cannot take into account the variance accounted for by these factors.

Conflict of Interest Statement: The authors report no conflict of interest.

REFERENCES

1. Abe T, Thiebaud RS, Loenneke JP. (2016). Age-related change in handgrip strength in men and women: is muscle quality a contributing factor? Age, 1;38(1):28. DOI: 10.1007/s11357-016-9891-4
2. Arellano, M. (2003). Panel Data Econometrics, Oxford University press, Oxford.
3. Bemben MG, Massey BH, Bemben DA, Misner JE, Boileau RA. (1991). Isometric muscle force production as a function of age in healthy 20- to 74-yr-old men. Medicine & Science in Sports & Exercise, 23:1302-1310. DOI:10.1249/00005768-199111000-00017
4. Beunen G, Malina RM. (2008). Growth, maturation and physical activity. In: Hebestreit H, and Bar-Or O, editors. The young athlete. Volume XIII of the encyclopaedia of sports medicine and IOC medical commission publication. Blackwell Publishing, P: 3-17. DOI:10.1002/9780470696255
5. Bishop P, Cureton K, Collins M. (1987). Sex difference in muscular strength in equally-trained men and women. Ergonomics, 30:675-687. DOI: 10.1080/00140138708969760
6. Cheuvront SN, Carter R, Deruisseau KC, Moffatt RJ. (2005). Running performance differences between men and women: an update. Sports Medicine, 35: 1017–24. DOI: 10.2165/00007256-200535120-00002
7. Dick, F. (2013). Athlete development – reflections on the pathway from potential to performance. New Studies in Athletics, 28(1/2): .47-54.
8. Frees, E. W. (2004). Longitudinal and panel data: analysis and application for the social sciences. Cambridge: Cambridge University Press. DOI: 10.1017/CBO9780511790928
9. Frontera WR, Hughes VA, Fielding RA, Fiatarone MA, Evans WJ, Roubenoff R. (2000). Aging of skeletal muscle: a 12-yr longitudinal study. Journal of Applied Physiology, 88:1321–1326. DOI: 10.1152/jappl.2000.88.4.1321
10. Goswami B, Roy AS, Dalui R, Bandyopadhyay A. (2014). Impact of pubertal growth on physical fitness. American Journal of Sports Science and Medicine, 2: 34–39. DOI: 10.12691/ajssm-2-5A-8
11. Hanley, B. (2014). The role of the European U23 Championships in the development of elite athletes. New Studies in Athletics, 29(3):41-56.
12. Haugen T, Solberg PA, Moran-Navarro R, Breitschädel F, Hopkins W, Foster C. (2018). Peak age and performance progression in world-class track-and-field athletes. International Journal of Sports Physiology and Performance, 13(9):1-24. DOI:10.1123/ijspp.2017-0682

ACCEPTED MANUSCRIPT

13. Hollings SC, Hopkins WG, Hume PA. (2014). Age at peak performance of successful track and field athletes. International Journal of Sports Science & Coaching, 9:651–662. doi.org/10.1260/1747-9541.9.4.651
14. Hsiao, Cheng, Why Panel Data? (2005). IEPR Working Paper No. 05.33, Available at SSRN: https://ssrn.com/abstract=820204 or http://dx.doi.org/10.2139/ssrn.820204
15. Hsiao, C. (2003). Analysis of panel data. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511754203 doi.org/10.1017/CBO9780511754203
16. https://www.worldathletics.org. (2020). Stats Zone. Records; Top lists: All-time Top lists.
17. Hulme A, Nielsen RO, Timpka T, Verhagen E, Finch C. (2017). Risk and protective factors for middle-and long-distance running-related injury. Sports Medicine, 47(5):869-86. doi: 10.1007/s40279-016-0636-4.
18. Knechtle B, & Nikolaidis, PT. (2018). The age of peak marathon performance in cross-country skiing—The "Engadin Ski Marathon". The Journal of Strength and Conditioning Research, 32(4), 1131-1136. DOI: 10.1519/JSC.0000000000001931
19. Koster A, Ding J, Stenholm S, Caserotti P, Houston DK, Nicklas BJ, You T, Lee JS, Visser M, Newman AB, Schwartz AV. (2011). Does the amount of fat mass predict age-related loss of lean mass, muscle strength, and muscle quality in older adults? Journals of Gerontology Series A: Biomedical Sciences and Medical Sciences. 66(8):888-95. doi: 10.1093/gerona/glr070
20. Larsson L, Grimby G, Karlsson J. (1979). Muscle strength and speed of movement in relation to age and muscle morphology. Journal of applied physiology: respiratory, environmental and exercise physiology, 46:451-456. DOI: 10.1152/jappl.1979.46.3.451
21. Malina R. (2014). Top 10 research questions related to growth and maturation of relevance to physical activity, performance, and fitness. Research quarterly for exercise and sport, 85: 157–173. doi.org/10.1080/02701367.2014.897592
22. Malina RM, Woynarowska B, Bielicki T, Beunen G, Eweld D, Geithner CA, Huang YC, Rogers DM. (1997). Prospective and retrospective longitudinal studies of the growth, maturation, and fitness of Polish youth active in sport. International Journal of Sports Medicine, 18:179-185. DOI: 10.1055/s-2007-972711
23. Matthews P. (2016). The International Track & Field Annuals. The Association of Track & Field Statisticians. IAAF. Athletics 2016 Book. Sports Books Ltd, 137-254.
24. Morgan DW, Bransford DR, Costill DL, Daniels JT, Howley ET, Krahenbuhl GS. (1995). Variation in the aerobic demand of running among trained and untrained subjects. Medicine & Science in Sports & Exercise, 27:404-409. DOI: 10.1249/00005768-199503000-00017
25. Nerlove, M. (2002). Essays in Panel Data Econometrics, Cambridge University of Press, Cambridge.
26. Nikolaidis, PT, Knechtle B. (2020). Performance in 100-km Ultramarathoners—At Which Age, It Reaches Its Peak? The Journal of Strength and Conditioning Research, 34(5), 1409-1415.
27. Noble TJ, Chapman RF. (2017). Elite African marathoners specialize earlier than elite non-African marathoners. International Journal of Sports Physiology and Performance, 10:1-19. DOI: 10.1123/ijspp.2017-0069
28. Ospina-Betancurt, J., Maria S. Zakynthinaki. (2020). Outstanding performances during elite-standard short and middle-distance finals and the hyperandrogenism regulation—A detailed analysis of Caster Semenya's results. Journal of Sports Sciences, 38:6, 703-709. https://doi.org/10.1080/02640414.2020.1727117
29. Ospina-Betancurt, J., Zakynthinaki, M. S., Martínes-Patiño, M. J., Cordente Martinez, C., & Rodríguez Fernández, C. (2018). Sex-differences in elite-performance track and field competition from 1983 to 2015. Journal of Sports Sciences, 36(11), 1262-1268. https://doi.org/10.1080/02640414.2017.1373197
30. Rogers MA, Evans WJ. (1993). Changes in skeletal muscle with aging: effects of exercise training. Exercise and Sport Sciences Reviews, 21:65-102. PMID: 8504850
31. Schulz, R. and Curnow, C. (1988). Peak Performance and Age among Superathletes: Track & Field, Swimming, Baseball, Tennis, and Golf. Journal of Gerontology, 43(5), 113-120. DOI: 10.1093/geronj/43.5.p113
32. Seiler S, De Koning JJ, Foster C. (2007). The fall and rise of the gender difference in elite anaerobic performance 1952–2006. Medicine & Science in Sports & Exercise, 39: 534–40. DOI: 10.1249/01.mss.0000247005.17342.2b
33. Smith, D.J. (2003). A Framework for Understanding the Training Process Leading to Elite Performance. Sports Medicine, 33(15), 1103-1126. DOI: 10.2165/00007256-200333150-00003
34. Solberg, PA Hopkins WG, Paulsen G and . Haugen TA. (2019). Peak Age and Performance Progression in World-Class Weightlifting and Powerlifting Athletes. International Journal of Sports Physiology and Performance, 14;10:1357-1363. doi.org/10.1123/ijspp.2019-0093
35. Storey A, Smith HK. (2012). Unique aspects of competitive weightlifting: performance, training and physiology. Sports Medicine, 42:769-790. DOI: 10.2165/11633000-000000000-00000
36. Thelen DG, Schultz AB, Alexander NB, Ashton-Miller JA. (1996). Effects of age on rapid ankle torque development. The Journals of Gerontology Series A Biological Sciences and Medical Sciences, 51:226-232. DOI: 10.1093/gerona/51a.5.m226
37. Thibault V, Guillaume M, Berthelot G, Helou NE, Schaal K, Quinquis L, et al. (2010). Women and men in sport performance: The gender gap has not evolved since 1983. Journal of Sports Science and Medicine, 9: 214–23. PMID: 24149688
38. Tonnessen E, Svendsen I, Olsen IC, Guttormsen A, Haugen T. (2015). Performance development in adolescent track and field athletes according to age, sex and sport discipline. PLoS ONE, 10:e0129014. DOI: 10.1371/journal.pone.0129014

ACCEPTED MANUSCRIPT

39. Weippert, M., Petelczyc, M., Thürkow, C., et al. (2020). Individual performance progression of German elite female and male middle-distance runners. European Journal of Sport Science, 1-7. DOI: 10.1080/17461391.2020.1736182
40. World Athletics (IAAF). (2016). The Referee Book. 14th edition. (Rule 187): P180.
41. Wu R, Delahunt E, Ditroilo M, Lowery M, De Vito G. (2016). Effects of age and sex on neuromuscular-mechanical determinants of muscle strength. Age, 1;38(3):57. DOI: 10.1007/s11357-016-9921-2

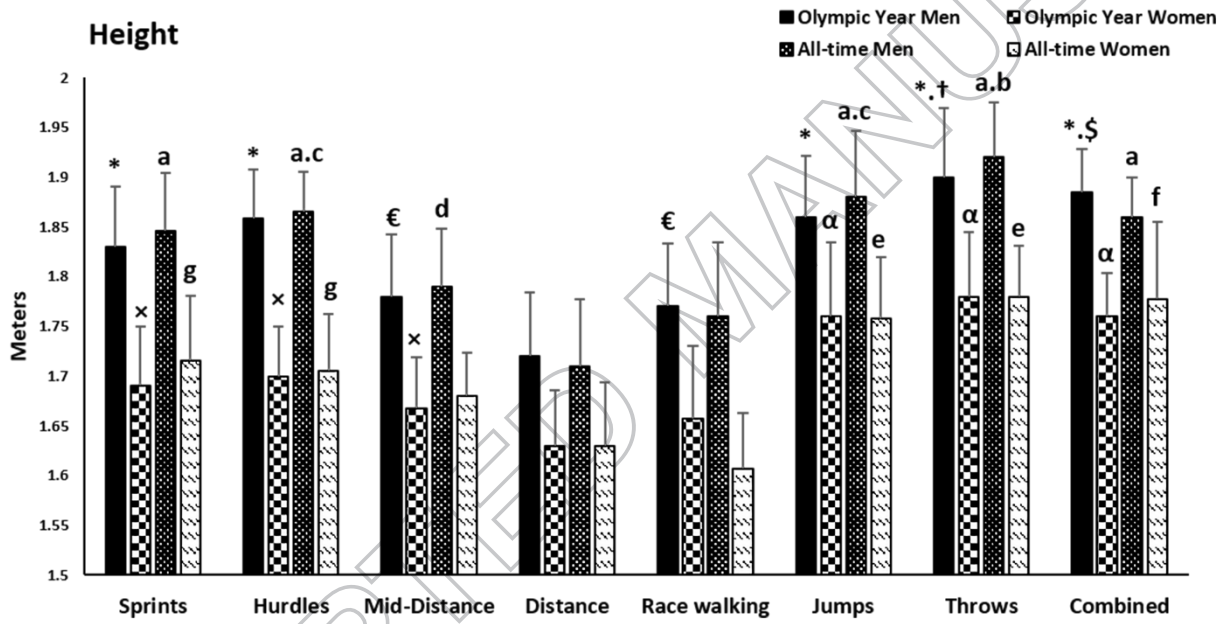


Figure 1. Height of Olympic year and All-time men and women top lists in 8 groups.

Olympic Year: M; *= significantly higher than mid-distance and distance men runners and race walkers. †= significantly higher than men sprinters, hurdlers and jumpers. **€**= significantly higher than men distance runners. **$**= significantly higher than men sprinters. **W; α**= significantly higher than women sprinters, hurdlers, mid-distance runners, distance runners and race walkers. ×= significantly higher than women distance runners. **All-time**: **M; a**= significantly higher than men distance and RW. **b**= significantly higher than men sprinters, hurdlers and mid-distance. **c**= significantly higher than men mid-distance. **d**= significantly higher than men distance. **W; e**= significantly higher than women sprinters, hurdlers, mid-distance distance and RW. **f**= significantly higher than women mid-distance, distance and RW. **g**= significantly higher than women distance and RW.

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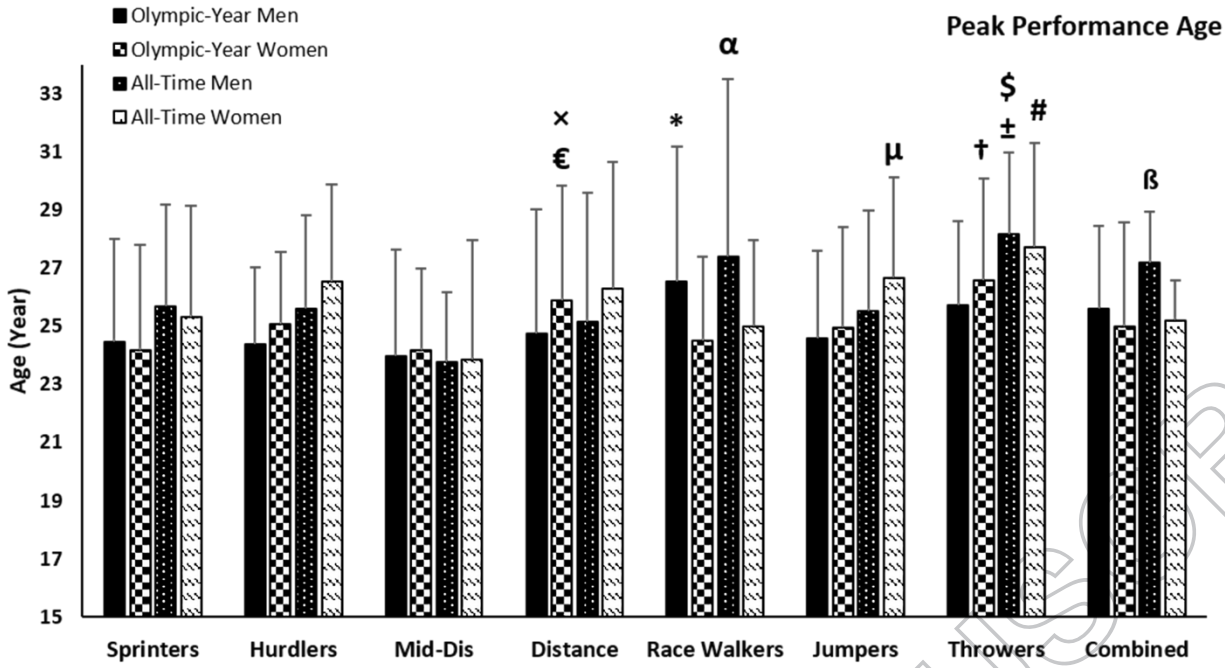


Figure 2. Peak performance ages of Olympic year top lists and all-time top 10 in 8 groups of men and women athletes.

*= Significantly different with Olympic year men distance runners. †= Significantly different with Olympic year women sprinters and mid-distance runners. ×= significantly different with Olympic year women sprinters. $= Significantly different with All-time men mid-distance runners, distance runners, and jumpers. α= significantly different with All-time men mid-distance runners. #= significantly different with All-time women mid-distance runners. €= Significantly different with Olympic year men distance runners. ß= significantly different with All-time women combined (Hep). ±= significantly different with Olympic year men throwers. µ= significantly different with Olympic year women jumpers.

Table 1. Results introduced by dynamic panel data using mixed top list results.

Groups			Results of model (dynamic panel data- P<0.05)*
Disciplines/Sex			
Sprints	100m	M	R_t=0.5295(R_{t-1}-m.R_{t-1})+0.1582(R_{t-2}-m.R_{t-2})+0.9984m.R_t; P<0.001, <0.05, <0.001
		W	R_t=0.5405(R_{t-1}-m.R_{t-1})+0.9977m.R_t; All were P<0.001
	200m	M	R_t=0.4917(R_{t-1}-m.R_{t-1})+0.1283(R_{t-2}-m.R_{t-2})+0.9985m.R_t; P<0.001, <0.05, <0.001
		W	R_t=0.4154(R_{t-1}-m.R_{t-1})+0.1913(R_{t-2}-m.R_{t-2})+0.9997m.R_t; P<0.001, <0.05, <0.001
	400m	M	R_t=0.5126(R_{t-1}-m.R_{t-1})+0.1444(R_{t-2}-m.R_{t-2})+0.9984m.R_t; P<0.001, <0.05, <0.001
		W	R_t=0.4046(R_{t-1}-m.R_{t-1})+0.1725(R_{t-2}-m.R_{t-2})+0.9986m.R_t; P<0.001, <0.05, <0.001
Hurdles	110mH	M	R_t=0.6486(R_{t-1}-m.R_{t-1})+1.0014m.R_t; All were P<0.001
	100mH	W	R_t=0.4171(R_{t-1}-m.R_{t-1})+0.9996m.R_t; All were P<0.001
	400mH	M	R_t=0.7211(R_{t-1}-m.R_{t-1})+0.2826(R_{t-2}-m.R_{t-2})+0.9195m.R_t; P<0.001, <0.05, <0.05
		W	R_t=0.3122(R_{t-1}-m.R_{t-1})+0.1737(R_{t-2}-m.R_{t-2})+1.0012m.R_t; P<0.05, <0.05, <0.001
Middle-distance	800m	M	R_t=0.4624(R_{t-1}-m.R_{t-1})+0.1352(R_{t-2}-m.R_{t-2})+0.9998m.R_t; P<0.001, <0.05, <0.001
		W	R_t=0.4431(R_{t-1}-m.R_{t-1})+0.1794(R_{t-2}-m.R_{t-2})+1.0005m.R_t; P<0.001, <0.05, <0.001
	1500m	M	R_t=0.4632(R_{t-1}-m.R_{t-1})+0.1845(R_{t-2}-m.R_{t-2})+1.0012m.R_t; All were P<0.001
		W	R_t=0.4212(R_{t-1}-m.R_{t-1})+0.1552(R_{t-2}-m.R_{t-2})+1.0011m.R_t; P<0.001, <0.05, <0.001
Distance	3000mSC	M	R_t=0.4862(R_{t-1}-m.R_{t-1})+0.1964(R_{t-2}-m.R_{t-2})+1.0006m.R_t; All were P<0.001
		W	R_t=0.3776(R_{t-1}-m.R_{t-1})+0.2384(R_{t-2}-m.R_{t-2})+0.9979m.R_t; <0.05, <0.05, <0.001
	5000m	M	R_t=0.4689(R_{t-1}-m.R_{t-1})+0.3025(R_{t-1}-R_{t-2})+1.0004m.R_t; P<0.05, 0.048, <0.001
		W	R_t=0.5670(R_{t-1}-m.R_{t-1})+0.1813(R_{t-2}-m.R_{t-2})+0.9986m.R_t; P<0.001, <0.05, <0.001
	10000m	M	R_t=0.3634(R_{t-1}-m.R_{t-1})+1.0001m.R_t; All were P<0.001
		W	R_t=0.3135(R_{t-1}-m.R_{t-1})+1.0014m.R_t; All were P<0.001
	42.195km	M	R_t=0.3904(R_{t-1}-m.R_{t-1})+1.0054m.R_t; P<0.05, <0.001
		W	R_t=0.3596(R_{t-1}-m.R_{t-1})+1.0035m.R_t; P<0.05, <0.001
	20 km	M	R_t=0.3271(R_{t-1}-m.R_{t-1})+0.9971m.R_t; All were P<0.001

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Race walking-RW	50km	W	R_t=0.5728(R_{t-1}-m.R_{t-1})+0.9998m.R_t; All were P<0.001
		M	R_t=0.3307(R_{t-1}-m.R_{t-1})+0.9989m. R_t; All were P<0.001
Jumps	Long jumps-LJ	M	R_t=0.4997(R_{t-1}-m.R_{t-1})+0.1737(R_{t-2}-m.R_{t-2})+0.9872m.R_t +0.0551H; All were P<0.001
		W	R_t=0.3852(R_{t-1}-m.R_{t-1})+0.2472(R_{t-2}-m.R_{t-2})+0.9898m.R_t +0.0358H; All were P<0.001
	Triple jump-TJ	M	R_t=0.5535(R_{t-1}-m.R_{t-1})+0.9968m.R_t +0.0332461H; P<0.001, <0.001, <0.05
		W	R_t=0.6179(R_{t-1}-m.R_{t-1})+0.9993m.R_t; All were P<0.001
	Height jump-HJ	M	R_t=0.4547(R_{t-1}-m.R_{t-1})+0.1726(R_{t-2}-m.R_{t-2})+1.0002m.R_t; P<0.001, <0.05, <0.001
		W	R_t=0.5983(R_{t-1}-m.R_{t-1})+0.1129(R_{t-2}-m.R_{t-2})+1.1000m.R_t; P<0.001, <0.05, <0.001
	Pole vault-PV	M	R_t=0.5632(R_{t-1}-m.R_{t-1})+0.2011(R_{t-2}-m.R_{t-2})+1.0014m.R_t; P<0.001, <0.05, <0.001
		W	R_t=0.5220(R_{t-1}-m.R_{t-1})+0.1765(R_{t-2}-m.R_{t-2})+1.0015m.R_t; P<0.001, <0.05, <0.001
Throws	Shot put-SP	M	R_t=0.4819(R_{t-1}-m.R_{t-1})+0.1982(R_{t-2}-m.R_{t-2})+0.9992m.R_t; All were P<0.001
		W	R_t=0.6432(R_{t-1}-m.R_{t-1})+0.1775(R_{t-2}-m.R_{t-2})+0.9943m.R_t; P<0.001, <0.05, <0.001
	Discus throw-DT	M	R_t=0.5295(R_{t-1}-m.R_{t-1})+0.9651m.R_t +0.0196W; P<0.001, <0.001, <0.05
		W	R_t=0.4671(R_{t-1}-m.R_{t-1})+0.1054(R_{t-2}-m.R_{t-2})+0.9950m.R_t; P<0.001, <0.05, <0.001
	Javelin throw-JT	M	R_t=0.5810(R_{t-1}-m.R_{t-1})+1.0011m.R_t; All were P<0.001
		W	R_t=0.5194(R_{t-1}-m.R_{t-1})+0.1662(R_{t-2}-m.R_{t-2})+1.0014m.R_t; P<0.001, v, <0.001
	Hammer throw-HT	M	R_t=0.3740(R_{t-1}-m.R_{t-1})+0.3607(R_{t-2}-m.R_{t-2})+0.9989m.R_t; All were P<0.001
		W	R_t=0.5241(R_{t-1}-m.R_{t-1})+0.1390(R_{t-2}-m.R_{t-2})+0.9988m.R_t; P<0.001, <0.05, <0.001
Combined	Decathlon-Dec	M	R_t=0.4165(R_{t-1}-m.R_{t-1})+0.2477(R_{t-2}-m.R_{t-2})+1.00m.R_t; P<0.001, <0.05, <0.001
	Heptathlon-Hep	W	R_t=0.3986(R_{t-1}-m.R_{t-1})+0.2343(R_{t-2}-m.R_{t-2})+0.9990m.R_t; P<0.001, <0.05, <0.001

*= Factors for every discipline were set at statistical significance of P<0.05. P-values are presented respectively. R_{t-1} is the best personal record one year ago, R_{t-2} is the best personal record two years ago, Rt.m is the average (mean) records of mixed Olympic year and All-time top lists records at certain age (Table 2).

Table 2. Performance progression (M±SD) of mixed Olympic year athletes and all-time in all disciplines (22 for Men and 21 for Women).

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Disc/ Age	100m Ms	100m Ws	200m Ms	200m Ws	400m Ms	400m Ws	110mHMs	100mHWs	400mHMs	400mHWs
13		12.39±0.57		25.70±1.66						
14		11.98±0.12		24.51±0.45		54.43±1.30				
15	11.37±0.26	11.90±0.35	21.81±0.75	24.01±0.37	48.20±1.35	54.75±1.22				59.94±2.94
16	10.82±0.19	11.76±0.37	21.45±0.43	23.79±0.54	47.65±1.33	53.29±0.77	14.60±0.57	14.08±0.55	52.89±1.37	58.34±1.61
17	10.55±0.15	11.59±0.28	21.26±0.58	23.60±0.65	46.88±0.92	53.15±1.59	14.25±0.43	13.99±0.37	50.96±1.32	58.53±2.03
18	10.37±0.14	11.46±0.22	20.78±0.33	23.43±0.67	46.06±0.86	52±0.92	13.84±0.38	13.72±0.34	51.36±1.58	58.14±1.99
19	10.32±0.20	11.38±0.29	20.66±0.49	23.11±0.55	46.06±1.19	51.39±1.18	13.78±0.32	13.32±0.29	50.25±1.08	56.63±1.69
20	10.20±0.20	11.23±0.23	20.47±0.47	22.86±0.55	45.35±0.99	50.86±0.97	13.56±0.30	13.01±0.22	49.75±1.62	56.30±1.43
21	10.09±0.21	11.20±0.22	20.31±0.54	22.66±0.47	44.87±0.62	50.31±1.19	13.36±0.30	12.86±0.20	48.86±1.16	55.55±1.19
22	10.00±0.13	11.05±0.16	20.11±0.40	22.39±0.40	44.71±0.75	50.19±0.98	13.26±0.21	12.78±0.22	48.60±1.00	54.78±0.93
23	9.96±0.16	11.13±0.28	20.09±0.36	22.46±0.46	44.61±0.62	50.08±0.87	13.29±0.24	12.73±0.17	48.22±0.73	54.45±0.76
24	9.97±0.11	10.97±0.16	20.12±0.31	22.43±0.47	44.73±0.76	50.07±1.18	13.23±0.21	12.62±0.19	48.41±0.72	54.45±0.99
25	9.97±0.12	11.07±0.25	20.04±0.31	22.53±0.54	44.95±0.53	49.89±1.02	13.20±0.19	12.54±0.19	48.45±0.82	54.08±1.09
26	9.97±0.15	10.99±0.21	20.18±0.38	22.29±0.29	44.82±0.53	50.03±0.70	13.21±0.20	12.54±0.12	48.16±0.86	53.77±0.84
27	9.94±0.13	10.97±0.15	20.24±0.36	22.46±0.58	45.02±0.85	49.96±1.02	13.15±0.20	12.49±0.13	48.14±0.67	53.89±1.12
28	9.98±0.13	10.96±0.10	20.10±0.45	22.33±0.34	44.55±0.63	49.84±0.92	13.17±0.16	12.48±0.10	48.39±0.86	53.97±1.02
29	9.87±0.09	10.92±0.20	20.25±0.62	22.34±0.44	44.87±1.03	49.98±0.58	13.13±0.13	12.59±0.18	47.92±0.52	53.71±1.00
30	9.93±0.13	10.95±0.15	20.14±0.17	22.70±0.65	44.97±0.94	50.18±0.75	13.18±0.17	12.68±0.26	47.97±0.34	54.40±0.50
31	9.94±0.10	11.01±0.15	20.14±0.22	22.31±0.35	44.89±1.03	50.65±1.01	13.20±0.20	12.64±0.20	48.40±0.64	54.40±0.81
32	9.94±0.20	10.94±0.34	20.12±0.36	22.45±0.52	44.82±0.82	50.48±0.52	13.31±0.27	12.65±0.20	48.75±0.87	54.92±0.70
33	9.90±0.20		20.35±0.85		44.18±0.56	50.45±0.28	13.11±0.14	12.52±0.11	49.02±0.99	57.06±1.41
34	9.92±0.08		20.30±0.35		45.15±0.35		13.11±0.10	12.77±0.46		
35					44.78±0.15		13.11±0.21	12.5±0.42		

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36					45.54±1.35		13.30±0.98			
37							13.41±0.15			

Disc / Age	**800m M** s	**800m W** s	**1500m M** min	**1500m W** min	**3000mSC M** min	**3000m SC W** min	**5000m M** min	**5000m W** min	**10000m M** min	**10000m W** min
13			4.61±0.15	5.01±0.26						
14		131.65±1.79	4.23±0.19	4.76±0.04						
15	113.96±6.60	129.57±2.15	4.01±0.08	4.60±0.16						
16	113.20±3.99	128.90±3.17	3.80±0.11	4.29±0.15		10.16±0.36	13.75±0.71	15.95±0.34		
17	107.56±2.54	127.22±4.05	3.70±0.10	4.21±0.13	8.62±0.23	9.99±0.44	13.62±0.56	15.50±0.46	29.18±0.38	
18	106.80±3.03	124.98±3.77	3.69±0.07	4.11±0.15	8.52±0.22	9.89±0.50	13.30±0.41	15.29±0.47	28.02±0.75	
19	105.35±1.83	122.28±4.65	3.61±0.09	4.14±0.11	8.29±0.20	9.81±0.47	13.27±0.36	15.09±0.36	27.84±0.52	31.76±0.69
20	104.45±1.31	121.87±3.34	3.58±0.06	4.07±0.13	8.18±0.12	9.64±0.35	13.19±0.28	14.98±0.46	27.48±0.58	30.56±0.67
21	104.37±1.64	121.76±3.16	3.52±0.05	4.06±0.11	8.15±0.13	9.55±0.16	12.96±0.12	14.82±0.29	27.38±0.58	31.19±0.21
22	104.09±1.72	120.40±2.30	3.54±0.05	4.07±0.12	8.07±0.12	9.39±0.20	13.07±0.20	14.90±0.43	27.30±0.51	31.14±0.89
23	104.05±1.59	120.52±2.80	3.54±0.05	4.04±0.10	8.11±0.11	9.26±0.12	13.06±0.19	14.87±0.30	27.16±0.35	30.96±0.51
24	104.22±1.52	118.76±1.45	3.53±0.05	4.01±0.07	8.12±0.10	9.24±0.16	13.09±0.21	14.87±0.42	27.15±0.44	31.13±0.67
25	103.57±1.01	118.28±1.95	3.54±0.05	4.01±0.06	8.12±0.12	9.21±0.10	13.11±0.21	14.74±0.34	27.36±0.51	31.19±0.84
26	104.01±0.81	117.65±1.95	3.54±0.06	4.03±0.04	8.08±0.11	9.13±0.11	13.13±0.17	14.77±0.25	27.45±0.52	30.96±0.47
27	103.70±0.56	117.88±1.68	3.53±0.05	4.05±0.05	8.09±0.10	9.19±0.26	13.10±0.20	14.78±0.24	27.16±0.32	30.81±0.49
28	103.59±1.04	117.53±1.47	3.52±0.04	4.04±0.05	8.13±0.13	9.26±0.23	13.09±0.18	14.73±0.35	27.17±0.53	30.97±0.44
29	104.17±1.47	118.49±1.23	3.52±0.03	4.01±0.09	8.04±0.11	9.24±0.19	13.18±0.27	14.73±0.20	27.00±0.30	30.77±0.67
30	103.94±1.53	117.77±1.85	3.49±0.04	4.04±0.09	8.16±0.14	9.27±0.11	12.97±0.10	14.79±0.28	27.16±0.33	30.95±0.83
31	105.85±1.58	118.04±2.17	3.49±0.01	4.07±0.10	8.10±0.19	9.34±0.01	13.04±0.11	14.86±0.28	27.28±0.53	31.14±0.80
32	104.45±0.73	117.04±2.41	3.52±0.05		8.09±0.09	9.37±0.07	13.03±0.13	14.88±0.43	27.10±0.38	30.72±0.42
33	106.28±2.51	117.79±1.56	3.56±0.03		8.11±0.12	9.56±0.23	12.98±0		27.61±0.64	30.72±1.68

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34		117.30±2.37	3.57±0.06		8.20±0.04		13.14±0.17		27.54±1.04	31.82±0.95
35		117.61±2.38								
36		117.81±0.52								

Continued

Disc/ Age	**42km M** min	**42km W** min	**20 km RW M** min	**20 km RW W** min	**50km RW M** min
16			87.37±10.04		
17			85.59±4.36		
18			84.20±4.43	88.91±0.87	
19	129.16±0.04	153.60±9.14	83.69±2.53	89.11±3.99	
20	128.87±2.67	147.15±6.78	81.14±2.08	90.15±3.48	239.93±11.93
21	126.26±1.04	146.52±6.90	80.80±1.48	89.09±3.07	232.90±9.56
22	126.23±1.94	145.82±5.24	80.57±1.57	88.47±2.98	230.31±8.05
23	127.19±1.40	144.44±3.61	80.09±1.37	88.19±2.27	227.06±6.63
24	127.01±1.47	143.83±3.79	80.22±1.41	87.16±1.53	226.97±6.81
25	126.01±1.35	143.03±4.73	80.29±1.47	87.43±1.68	225.28±5.56
26	125.81±1.36	144.74±3.50	79.89±1.07	86.72±1.87	223.64±4.27
27	126.05±1.33	144.33±3.33	80.12±1.79	87.54±1.62	224.10±3.35
28	126.57±1.74	143.59±3.07	80.40±1.33	86.71±1.53	222.52±4.23
29	126.17±1.64	143.04±3.30	80.13±1.46	88.29±1.36	222.67±3.22
30	126.24±2.13	142.33±3.07	79.54±1.16	87.29±1.00	222.87±3.71
31	126.83±1.97	143.72±1.59	80.42±2.26	87.78±2.39	221.84±3.58
32	128.11±4.01	143.28±3.25	80.45±0.69	88.00±1.05	222.72±5.03
33	126.44±2.34	143.10±1.84	81.12±0.19	90.26±2.24	223.23±2.00
34		143.80±2.25	79.88±0.55	88.17±1.80	224.78±4.17
35		142.89±3.59	83.23±1.76	87.71±1.90	222.30±4.34
36				87.74±0.43	221.66±6.13
37					229.09±6.50
38					222.21±4.18
39					230.25±8.66

Continued

Disc/ Age	**Long Jump M** m	**Long Jump W** m	**Triple Jump M** m	**Triple Jump W** m	**High Jump M** m	**High Jump W** m	**Pole Vault M** m	**Pole Vault W** m
12						1.52±0.09		3.08±0.32
13		5.29±0.18				1.64±0.06		3.63±0.33
14	6.66±0.14	5.76±0.14	14.79±0.24		1.71±0.13	1.69±0.08	3.40±0.56	4.01±0.24
15	6.76±0.54	6.03±0.21	14.79±0.47	12.49±0.79	1.91±0.19	1.74±0.07	4.07±0.57	3.86±0.45
16	7.45±0.45	6.11±0.25	15.16±0.71	12.72±0.12	2.10±0.09	1.80±0.05	4.64±0.37	3.97±0.24
17	7.43±0.45	6.27±0.23	15.87±0.48	13.03±0.19	2.17±0.09	1.85±0.06	4.96±0.43	4.04±0.24
18	7.62±0.35	6.33±0.26	16.18±0.40	13.48±0.33	2.20±0.07	1.88±0.05	5.17±0.39	4.19±0.21
19	7.83±0.31	6.49±0.25	16.68±0.45	13.72±0.39	2.26±0.05	1.91±0.04	5.44±0.32	4.26±0.22
20	8.00±0.33	6.69±0.24	17.03±0.47	13.77±0.34	2.31±0.05	1.94±0.05	5.57±0.24	4.39±0.21
21	8.13±0.27	6.78±0.21	17.20±0.51	14.09±0.43	2.32±0.05	1.95±0.05	5.69±0.17	4.44±0.22
22	8.19±0.29	6.85±0.23	17.20±0.42	14.22±0.30	2.32±0.05	1.96±0.05	5.81±0.12	4.49±0.22

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23	8.26±0.26	6.86±0.24	17.29±0.31	14.51±0.41	2.34±0.04	1.98±0.04	5.84±0.11	4.52±0.18
24	8.25±0.18	6.94±0.21	17.52±0.20	14.55±0.41	2.34±0.04	1.98±0.05	5.83±0.11	4.72±0.11
25	8.33±0.18	6.98±0.23	17.48±0.33	14.60±0.39	2.35±0.03	1.99±0.04	5.84±0.11	4.68±0.13
26	8.36±0.19	7.03±0.28	17.42±0.30	14.65±0.30	2.35±0.04	2.00±0.05	5.87±0.12	4.72±0.16
27	8.30±0.21	6.98±0.20	17.25±0.25	14.74±0.31	2.35±0.03	2.00±0.04	5.81±0.17	4.72±0.15
28	8.36±0.22	7.00±0.23	17.23±0.22	14.72±0.36	2.34±0.04	1.99±0.04	5.87±0.15	4.75±0.11
29	8.28±0.24	6.88±0.19	17.23±0.51	14.64±0.48	2.32±0.03	1.99±0.05	5.90±0.13	4.76±0.14
30	8.29±0.25	6.88±0.25	17.18±0.33	14.69±0.48	2.32±0.03	2.00±0.03	5.85±0.11	4.75±0.08
31	8.34±0.24	6.93±0.17	17.18±0.33	14.60±0.44	2.33±0.02	1.96±0.05	5.84±0.17	4.75±0.12
32	8.31±0.33	6.89±0.27	17.31±0.32	14.69±0.50	2.29±0.03	1.96±0.05	5.87±0.17	4.73±0.06
33	8.32±0.24	6.72±0.11	17.22±0.31	14.43±0.35	2.25±0.09	1.98±0.03	5.87±0.19	4.72±0.13
34	8.23±0.16	7.00±0.18	17.12±0.55	14.26±0.41	2.30±0	1.99±0.02		4.76±0.13
35	8.34±0.15	6.83±0.08	17.37±0.53	14.24±0.29	2.25±0.06	1.96±0.05		
36	8.03±0.08	6.72±0.22	17.23±0.49		2.26±0.01			
37	7.79±0.63	6.52±0.44	17.23±0.53					
38	7.76±0.30							

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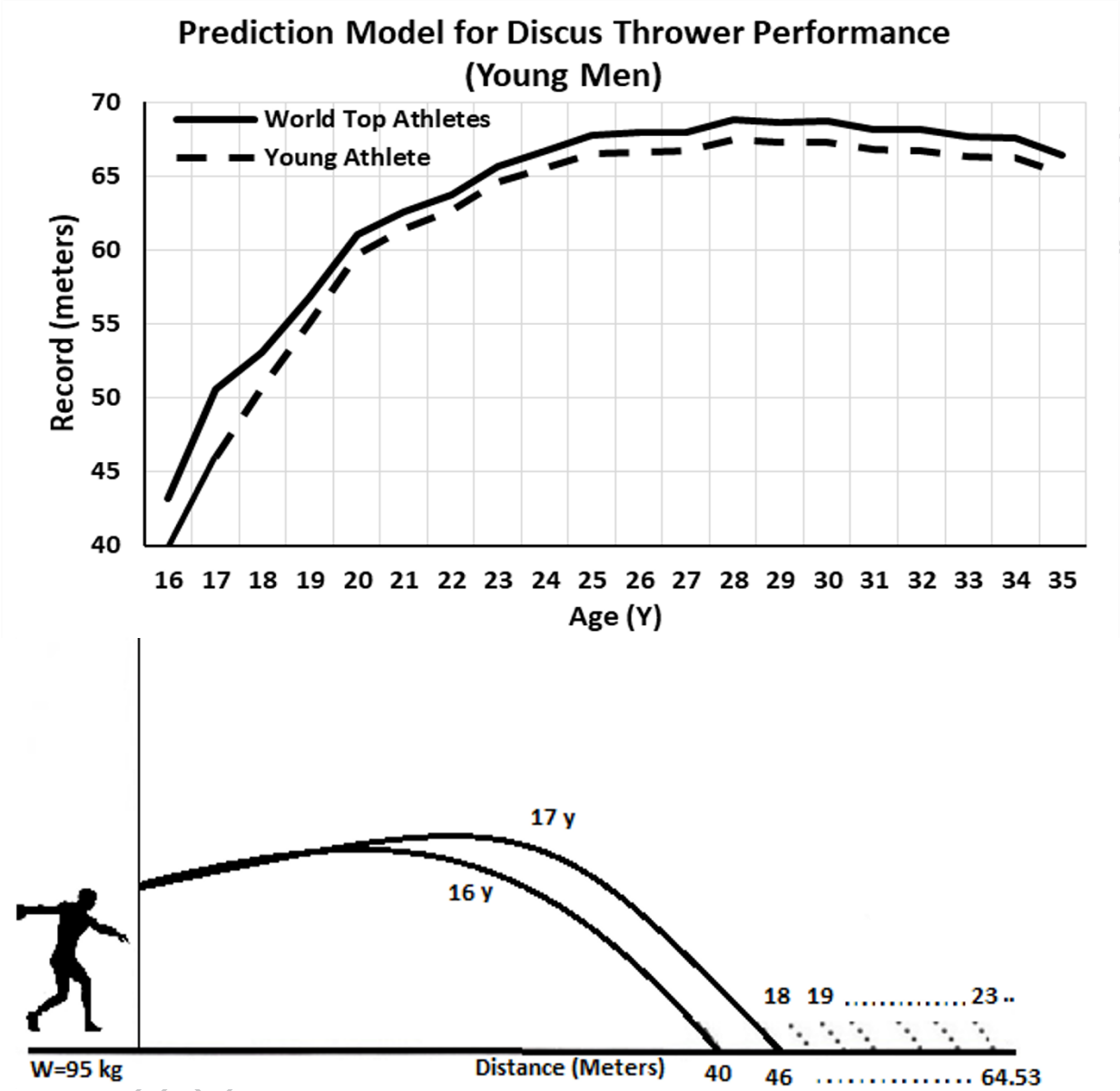
Disc/ Age	Shot Put M m	Shot Put W m	Discus.T M m	Discus.T W m	Javelin.T M m	Javelin.T W m	Hammer. T M m	Hammer. T W m	Decathlon M scores	Heptathlon W scores
14				45.19±0.46		47.81±6.61				
15		14.37±0.49		47.04±1.24		48.05±4.92				4948±345
16		15.10±0.60	43.20±5.70	48.95±4.07	58.92±3.33	49.89±4.63	58.95±7.00	55.25±9.40		5312±185
17	16.59±2.33	16.03±1.15	50.60±5.64	54.47±5.61	68.87±4.69	51.82±4.59	65.35±4.07	57.42±7.45		5453±359
18	17.37±1.90	16.42±1.48	53.09±3.54	56.96±5.60	72.26±5.23	52.91±3.95	65.09±5.66	61.05±5.93	6988±393	5553±327
19	18.28±1.59	17.75±1.10	56.86±1.95	61.53±4.68	77.51±3.71	56.33±4.01	68.66±4.55	63.13±5.50	7532±299	5773±397
20	18.13±1.62	18.37±1.43	61.05±3.22	63.38±5.25	79.02±3.45	58.09±4.73	71.55±4.47	66.29±4.30	7908±250	5984±425
21	19.49±1.41	18.70±1.10	62.57±2.70	64.29±3.54	82.31±2.61	60.34±4.06	74.71±3.27	68.40±3.70	8119±305	6165±333
22	20.38±1.22	19.16±1.44	63.76±2.79	66.66±3.09	83.84±3.28	61.54±4.86	75.98±3.42	70.55±3.20	8287±221	6194±350
23	20.82±0.92	19.40±1.21	65.67±1.56	66.57±3.57	85.86±3.41	63.25±3.33	77.98±2.83	72.10±2.60	8386±125	6326±268
24	21.26±0.92	19.85±1.27	66.71±1.61	67.07±4.13	85.95±3.76	63.39±3.55	78.87±2.55	73.74±3.24	8495±16	6522±312
25	21.39±0.58	19.96±1.37	67.72±2.02	68.38±3.93	86.41±3.81	63.78±4.00	79.27±2.55	74.21±2.50	8567±207	6466±298
26	21.47±0.74	20.05±1.19	67.91±2.14	68.34±3.36	88.38±3.68	64.21±3.52	80.26±1.94	74.82±2.31	8555±208	6457±307
27	21.67±0.56	20.27±1.42	67.98±2.59	67.28±3.01	88.36±4.59	64.93±3.27	81.20±2.39	74.70±2.15	8618±252	6582±213
28	21.48±0.69	20.51±1.07	68.77±2.51	67.06±3.05	88.17±3.02	65.28±2.19	81.77±2.73	75.86±2.56	8680±162	6506±214
29	21.40±0.51	20.29±1.14	68.61±2.22	67.32±3.62	88.58±3.15	67.20±1.53	80.90±3.34	75.25±3.00	8626±244	6517±125
30	21.64±0.67	20.18±0.82	68.70±2.32	67.28±4.15	89.15±4.41	66.05±2.67	80.96±3.03	76.16±2.97	8510±250	6533±252
31	21.70±0.71	20.10±0.94	68.13±2.02	67.51±4.11	88.41±2.95	65.61±1.88	82.32±2.73	75.31±4.35	8531±243	6538±227
32	21.71±0.56	20.38±0.89	68.11±1.54	65.01±5.45	88.22±1.34	65.74±2.48	81.34±2.33	75.07±3.88	8425±232	6494±245
33	21.51±0.61	20.25±1.44	67.65±1.80	67.05±2.67	88.06±1.83	65.83±1.94	80.65±2.40	74.63±2.68	8370±248	6245±152
34	21.44±0.61	20.39±1.26	67.53±2.86	67.35±1.51	88.01±1.87	65.94±1.83	80.30±1.95	74.21±1.97	8185±167	
35	21.57±0.56	19.65±1.74	66.45±2.36	64.88±0.88		65.87±0.95	80.63±2.47		8184±231	
36	21.00±1.28	19.45±1.49	66.67±2.79				79.64±2.64			

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37	20.56±0.99	19.79±1.01	67.10±2.26				79.74±2.54			
38	20.68±0.99	19.25±1.68	67.05±2.41				78.74±2.83			
39			67.38±1.62				78.68±2.40			
40			66.10±3.37							

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$Rt=0.4371939(Rt\text{-}1\text{-}m.Rt\text{-}1) +0.1263533(Rt\text{-}2\text{-}m.Rt\text{-}2)+0.9590520m.Rt +0.0230944w; Rt_{23}=64.53$

Graphical Abstract

ACCEPT