Sports Training

Limits of athletic performance by age: an analysis through the best performances in athletic jumping events

René Brenzikofer[1], Júlia Barreira[1], Denise Vaz Macedo[2]

[1]Universidade Estadual de Campinas, Faculdade de Educação Física, Departamento de Ciências do Esporte, Campinas, SP, Brazil; [2]Universidade Estadual de Campinas, Instituto de Biologia, Departamento de Bioquímica e Biologia Tecidual, Campinas, SP, Brazil.

Associate Editor: Universidade Estadual Paulista, Departamento de Educação Física, Instituto de Biociências, Rio Claro, SP, Brazil.

Abstract - Aim: This study aimed to investigate and interpret the upper limit of recorded performances in the four jumping events according to the age of the athletes. **Methods:** A phenomenological and its corresponding mathematical model were developed to describe the age-related upper limit of performance according to sex and competition level (national or world-class), comprising 16 groups. Our model was based on three hypothesised parameters: i) a maximum performance level (*Pmax*) for each jumping event; ii) the rate of performance growth which is proportional to what remains to reach *Pmax* (constant of proportionality *K*); iii) a starting age (T_0) for its application. The resulting exponential mathematical model integrates the three parameters, which were quantified by fitting the model to the performance data. **Results:** All the 16 limit curves were efficiently fitted within the upper borders of the data over the entire analysed age range. The adequacy of the model and its hypotheses were validated through the R^2 of the fitted curves (mean = 0.90, max/min = 0.98/0.75), and the fitting of the 48 parameters were qualified through their 95% confidence intervals. An interpretation of the model's parameters is proposed and comparisons of the age-related performance between Brazilian and international athletes are exhibited. A linear relation between *To* and 1/*K* was observed. **Conclusion:** The limit curves may be used as a reference for age-related improvement in athletic performance. The comparison between the limit curves of national and world-class competition levels reveals an original tool for comparing the effectiveness of the country's infrastructures and sports policies.

Keywords: model, development, training, coaching, policy.

Introduction

The upper limit of performance in any sport is generated by individual performances and affected by local conditions offered to athletes. The path that takes a child from an amateur to a skilled athlete is long and complex. Several factors contribute to this complexity, such as the effects of training, technical skills, physical maturity, psychological aspects, access to infrastructure, and local sports policies. In addition, the athlete's mental state on the day of competition plays a significant role in their performance. These factors lead to the high variability of the marks in competitions and significant differences in performance development from youth to adulthood[1,2], making the analysis of elite athlete development a challenge for sports scientists and managers. To achieve reliable data characterising performance evolution should be reproducible. Several ways to improve the knowledge about the learning/training processes of young athletes were tracked. For example, studies describe tools based on fitted mathematical models to investigate athlete performance over time as presented below.

Limitations when analysing individual longitudinal performance may be overcome by grouping results or using more extensive sets of athletes. Haugen et al.[3] show interesting results for senior elite athletes by quantifying maximum performance according to age by adjusting a curve to the annual results. The results obtained by different individuals may also reveal patterns of performance development. Tønnessen et al.[4] compared the evolution of the one hundred best performances in racing and jumping events of young Norwegians of both sexes between 11 and 18 years old. Although the authors highlighted the sex-specific differences in the rate of performance development, the performances were analysed through age groups of one-year range by using mean and standard deviation. These parameters mix athletes with different stages of maturation and reduce the study's sensitivity and reliability.

The heterogeneity of the individual scores or the heterogeneity of small groups along time hinders their use as an efficient source to provide a better understanding of the performance evolution. Moreover, the analysis of compilations of track and field records could potentially clarify how athletes develop their skills over time. A set of records defines a limit curve or borderline of performances as a function of age. By representing the "human limits" of performance in each age group, these borderlines form a relatively stable frontier in time and are composed of the marks from different athletes. As suggested by Moore[5] "the records analysed here comprise the marks of many individual athletes, but they can be thought as those set by a 'super' runner; one who is in top condition throughout his life span." The author selected sex-specific track and field records obtained throughout the lifetime of athletes and fitted a bi-exponential model to the data. Likewise, in Berthelot et al.[6] and Marck et al.[7], the same model was used to describe the performance of athletes throughout the lifespan in track events at peak performances. Similarly, Knechtle et al.[8] investigated the relationship between race times and age by using the world single age records of athletes from different countries, from 5 km to marathon through a 4th order-polynomial model to fit statistically well-defined performance versus age curves. Other studies used mathematical models to analyse the age dependence of maximum sports performance during the decay phase in the master category[9-12]. Although the model's curves adjusted well to the data in all cited studies, the quantified parameters were ignored, given that only the fitted curves were analysed.

A model is a simplified representation of a phenomenon, which has similar characteristics to the imitated object. Models allow the simulation and analysis of situations that would not be possible with the real event. Mathematical models and their parameters do not automatically represent natural phenomena. These relationships need to be established. We consider two types of models for the same object; (a) the phenomenological model, which seeks to capture the essence of the phenomenon to be analysed and the intervening variables, and (b) the related mathematical model, defined through hypotheses and equations based on parameters. These parameters are mostly related to the variables of the phenomenon and can be quantified by fitting the model to the experimental data generated. The quality of the parameter adjustments, verified through specific statistical tests, certifies the validity of the hypotheses, and the model.

The studies mentioned above provide valuable information on the patterns of age-related performance throughout life and in the aging phase. Most of the studies assured the statistical quality of the fitted curves of performance data. These curves were analysed, for example, to determine values and age of peak performance. However, there is a lack of relationship between the used mathematical models and the analysed sports disciplines, particularly, for this study, in the field of learning/training phases of young athletes. Furthermore, the studies above investigated the performance of international athletes providing valuable information for coaches and managers from other nationalities. To the best of our knowledge, no study has investigated the age-related performance of Brazilian athletes and compared them with the international ones.

One difficulty in studying the performance progress of young athletes is the rule changes that occur according to categories and that create discontinuities in the results. The athletic jumping events are exceptions in this context because they always measure an achieved distance. These events are subdivided into horizontal (long and triple), and vertical (high and pole vault) jumps. There are important differences in the technical and physiological characteristics of the four jumping events, even with similar physical strength and power requirements. We hypothesise that a unique model (phenomenological and the corresponding mathematical) could be used to characterise the performance improvement in different jumping events and categories. If this is possible, the curves and parameters generated by a single model will allow the comparison of the performance improvement in various disciplines, by athletes of different sexes and countries. As a first exploration of the theme, we will investigate and compare gender-based performances between Brazilians national performances and world-class performances.

This study aimed to investigate and interpret the upper limit of performances in the four jumping events according to athlete's age. For this, we proposed a model to describe the age-related behaviour of the best performances of athlete groups based on gender and competition levels, in the four athletic jumping events. The model was based on the principle that athletes develop faster when the further he or she is from the maximum performance. Interpreting the parameters that characterise our proposed limit curves for each investigated jump category (gender and competition level) can provide new elements for a better understanding of the performance development in athletic jumping events, contributing to the knowledge on the learning/training phase of young athletes.

Like previous works, this study is based on the exponential model. However, it advances with the current knowledge by proposing i) the interpretation of the model' parameters; ii) the comparison of the age-related performance between Brazilian and international athletes.

Methods

Phenomenological and mathematical model

The model proposed in this study is based on the principle that as athletes adapt to training, the rate of performance growth decreases. As a result, the closer the athletes are to maximum human performance, the more difficult it is to promote improvements in their performance through training.

The developed mathematical model quantifies the phenomenon described above aiming to equate a limit curve, or borderline, that represents the best age-related performances and is based on three hypotheses:

1) There is maximum performance for any time (P_{max}).
2) The rate of increase in performance is proportional to what remains to reach P_{max} (constant of proportionality K).
3) The model considers a starting age (T_0) for its application.

Equation (1) represents the model resulting from the application of the hypotheses:

$$p(t) = P_{max} * \left(1 - e^{-K*(t-T_0)}\right) \qquad (1)$$

This equation describes the proposed exponential model for performance (p) of the boundary curve in relation to the athlete's age (t). For each jumping event, sex, and competition level (national or international), $p(t)$ appears as a function of the maximum performance (P_{max}), the constant of proportionality (K) of the rate of increase in performance, and the model's initial age (T_0). In each jump category, the three parameters can be quantified by fitting Equation (1) to a selection of the best marks registered in official competitions.

Predicted age for elite athletes

The peak performance of an elite athlete in track and field is achieved at the beginning of the twenties[13]. Our model describes the ascending phase of performance evolution and does not predict any peak performance, but an asymptote at P_{max}. Thus, based on the limit curve (Equation (1)), we can predict at which age the "elite athlete" would have achieved any fraction of P_{max}, for example, 95%. Therefore, a parameter called "95%*Age*" was deduced from Equation (1) and can be quantified by Equation (2) for each jump category.

$$95\%Age = T_0 + \frac{3}{K} \qquad (2)$$

It is worth noting that Equation (2) is the product of dividing Equation (1) by P_{max} and applying the logarithmic function.

Samples

To compose the database, we used two purposive samplings aiming to select the best performances from the four jumping styles, one at national and the other at international levels. The national database included the results and dates of birth of athletes who had won at least one official competition in Brazil in the period from 2000 to 2014. To assure that all best performances were collected, including the non-podiums, data were completed with all individual results of these champions in official competitions throughout their sports career from the age of 14 years old onwards. All data were collected from the official website of the Brazilian Athletics Confederation (CBAt).

The world-class athletes' database included all the three best performances in the World Championships and Olympic Games, from junior to adult categories that took place in the same period. The performances, competition dates, and the athletes' dates of birth were collected from the official website of the International Association of Athletics Federations (IAAF).

Table 1 presents the distribution of the 15,345 data points collected among the 16 different groups (gender-specific national and world-class level athletes at four athletic jumping events). To facilitate text reading, jumps are presented in the following order: long jump, high jump, triple jump, and pole vault.

As we used only publicly available data, this study did not require approval by the university's ethics committee. Thus, the participants did not sign any informed consent forms.

Selection of best performances

The performance limit curve for each jump category is obtained by fitting Equation (1) to a selection of the best results. In the case of national marks, comprising 14'577 scores, a set of procedures were developed to select a sample that included all performances closest to borderline for each age. To identify the best performances of each group, the national database was divided into age classes with a duration of six months each. The three best performances of each age class were selected. Then, a new selection was carried out by applying the same procedure

Table 1 - Amount of data collected and athletes in each athletic event in the period from 2000 to 2014.

	National				World Class			
	Female		Male		Female		Male	
	Results	Athletes	Results	Athletes	Results	Athletes	Results	Athletes
Long Jump	2359	49	2766	59	96	56	96	70
High Jump	1257	34	1304	51	99	59	99	65
Triple Jump	1329	28	2033	45	93	49	93	73
Pole Vault	1726	31	1803	43	96	58	96	58

to new age classes shifted by three months. The marks obtained by the two selections were combined, and when the same performance was selected by the two procedures, only one was kept avoiding duplication. The world-class sample corresponding to international marks was composed of all the collected data because all of them are podium scores. These two samples of best results were used to adjust the boundary curves to the national and world-class level of each event and sex. The procedures described below were automated to ensure identical analyses for the 16 study groups.

Boundary curve adjustment

To quantify and qualify the performance boundary curve in each of the 16 study groups, the model's parameter adjustment was conducted in two successive stages. The selected samples of the best international and national performances from each group were used for a first adjustment of the model's parameters. This adjusted curve divided each sample into two data sets of a similar size, one with performances above the adjusted curve and another with performances below it. The first set (above) was used as a new sample for fitting the same model to quantify the final parameters of the boundary curve.

Model quality and statistical analysis

The adequacy of the model and validity of the three hypotheses are certified through the quality of the boundary curves' fit to the data. These adjustments and their residual values were analysed graphically and by using statistical parameters. The normality and homoscedasticity of the residuals of the boundary curves' final fit were analysed using Lilliefors and Engle's Arch statistical tests, respectively. The quality of the curves' adjustment was quantified by the value of the coefficient of determination (R^2), and the residuals' standard deviation was expressed as a P_{max} percentage (SD%). The uncertainty affecting each of the parameters (P_{max}, K, and T_0) was expressed by their 95% confidence interval (95% CI), determined using the bootstrap method[14]. The ANOVA test was used for "95%Age" comparisons between groups and the relationship between K and T_0 was explored through a scatter plot, regression line, and Pearson coefficient of correlation (r). The significance level was set at 0.05 for the quantitative analyses. All analyses and graphs for this study were executed in MATLAB® 2010 (The MathWorks Inc., Massachusetts, USA).

Results

Figure 1 presents the initial set of official marks obtained during the careers of male and female national champions from 2000 to 2014 plus the limit curve adjusted to the sample of best national performances by age for four types of jumps.

The graphs show the limit curves appropriately fitting the upper borders of the data over the entire age range for the different events and sexes. The model shows performances with rapid initial growth followed by a stabilization trend, generally for those over 20 years of age, regardless of the athletes' sex, with exceptions for the triple jump for males and the pole vault jump for females.

Figure 2 compares the limit curves that were adjusted for the best national and world-class male and female performances for each event. The curves start at the age when the first official results were collected.

The graphs show significant differences in the evolution of best female, male, national and world-class performances. The behavior of the limit curves of male and female world-class performance in comparison with national performance varies greatly depending on the type of jump analysed. In all cases, the initial performance of the world-class limit curve is above the beginning of the corresponding national curves.

Table 2 presents the values of adjusted parameters P_{max}, K, T_0, and their 95% confidence intervals. Additionally, the "95%*Age*" was calculated for all limit curves. The statistical variables (R^2, SD%) that evaluate adjustment quality are also presented for all limit curves.

High R^2 values and low SD% in the 16 groups confirm the suitability of the model, the hypotheses, and the selection process for best performances. The 95% confidence intervals show good reliability for the three parameters in all groups.

The P_{max} parameter differentiates the four types of jumps and quantifies the model's maximum performance for each category. The K parameter quantifies the rate of growth of the performance. By comparing the K of national and world-class samples, higher values were found for nationals in most jumps. The range of K values adjusted to the national data was approximately three-fold higher than the range of K corresponding to world-class athletes. Male national and world-class samples showed higher K values than female samples for most jumps. The T_0 parameter, defined as the initial age for the model (zero performance), ranged from 4.3 to 13.1 years old and was extrapolated through fits to data of athletes over 14 years old. The T_0 values were higher for men than for women, except for the national triple jump and world-class long jump. In comparison to female T_0, only that of the national triple jump was higher compared to its world-class counterpart.

In relation to the "95%Age" parameter (Table 2), it was found that 14 of 16 categories reached 95% of P_{max} at 95%Age = 19.0 ± 1.6 years old (mean ± SD) regardless of sex, of being associated with a national or world-class level, or of the jumping event ($p = 0.1$). Based on this finding, we calculated the average of "95%Age", defined as <95%Age>, and rewrote the Equation (2) as

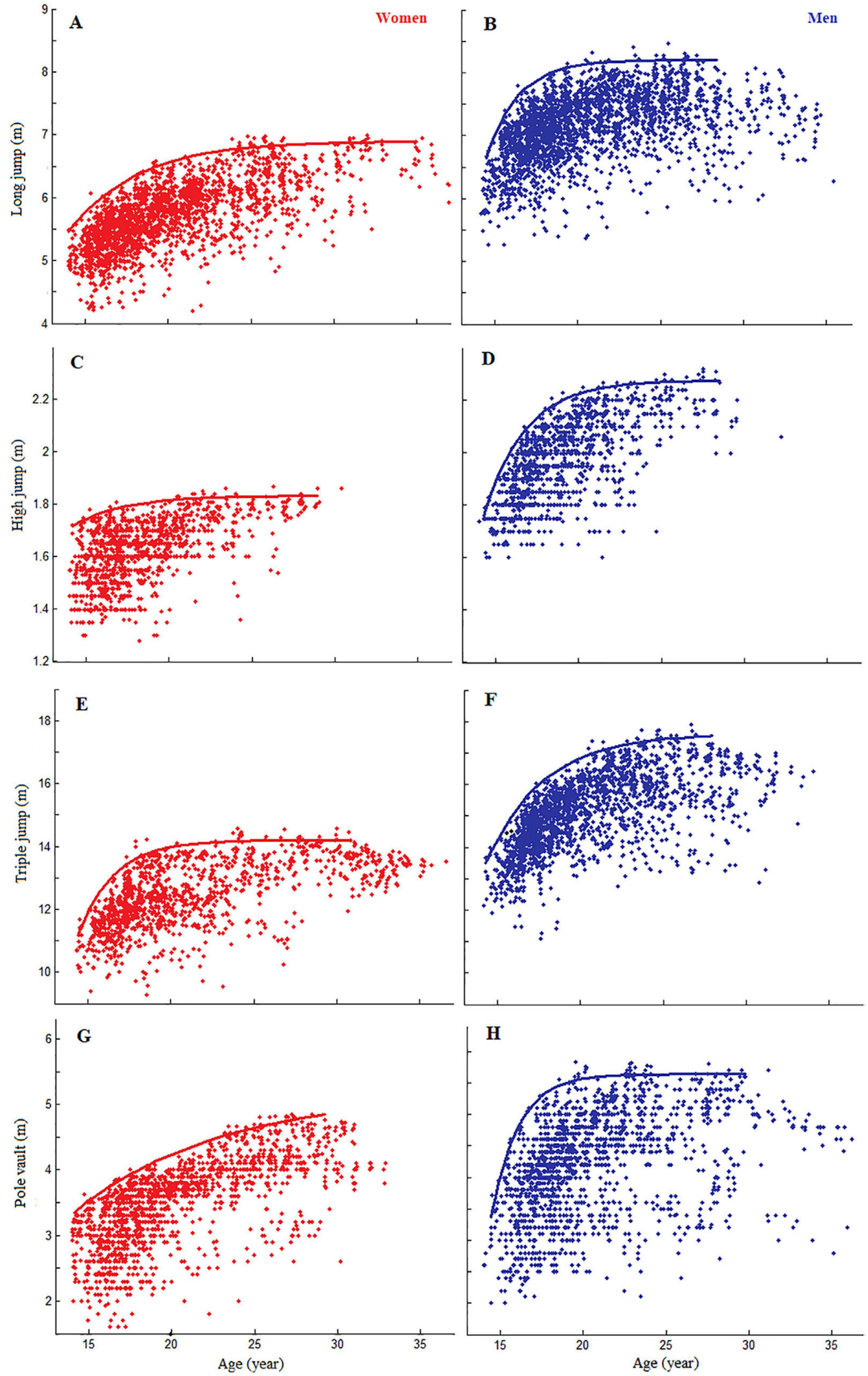

Figure 1 - Limit curves adjusted for best marks obtained by national athletes in official competitions in four athletic jumping events by age. (A) Women long jump; (B) Men long jump; (C) Women high jump; (D) Men high jump; (E) Women triple jump; (F) Men triple jump; (G) Women pole vault; (H) Men pole vault.

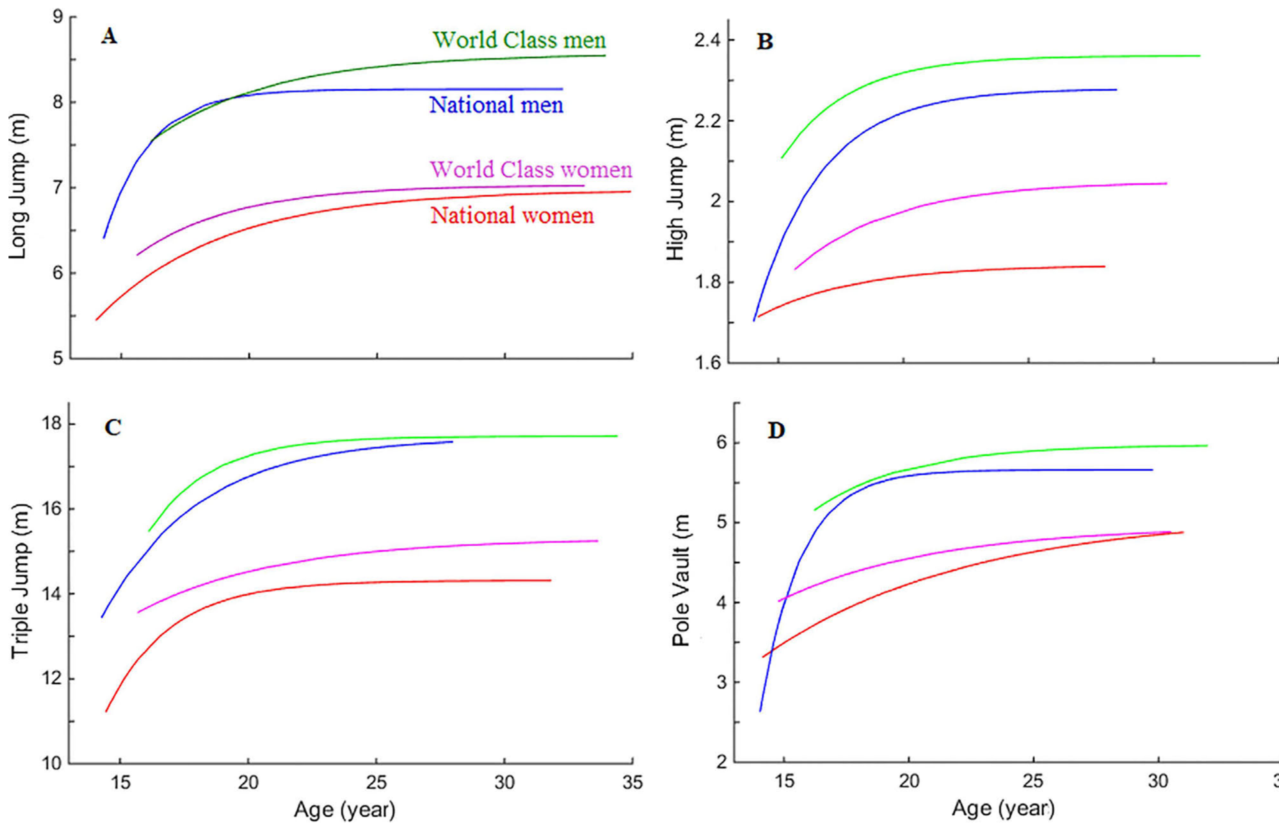

Figure 2 - Curves of best national and world-class male and female age-related performances in four athletic jumping events. (A) Long jump; (B) High jump; (C) Triple jump; (D) Pole vault.

$$T_0 = 95\%Age - 3 * \frac{1}{K} \tag{3}$$

which is the equation of a straight line connecting the two parameters T_0 and $1/K$ in all categories.

Figure 3 shows the graph of T_0 as a function of $1/K$ with the least square fitted line for 14 pairs of data (·) and resulting in a Pearson correlation coefficient of $r = -0.94$. The two outliers (+), women's national pole vault and national high jump were not used in the line fitting.

The fitting of the line in Figure 3 shows an intercept that is compatible with <95%Age> ($p > 0.05$), but with a higher slope than predicted. The graphic shows that when T_0 occurs earlier, variable $1/K$ shows higher values and K lower values, which indicates a slower performance growth. However, when T_0 occurs later, variable $1/K$ is reduced, and K increases, resulting in faster performance growth.

Discussion

The results presented here confirm the validity of the proposed model in characterising the ascending age-related behavior of the best performances of male and female, national and world-class athletes, in four jumping types. The mathematical model based on the three hypotheses was tested by the limit curves which adequately represent the borderlines of the data through the entire age range, for all 16 groups, as shown for national athletes in Figure 1. The outcomes of the statistical tests shown in Table 2, *i.e.* high values of R^2, low values of SD%, and reduced 95% CI of the three parameters, qualifies the mathematical model's validity in all groups.

Although the borderlines are not originated by individual athletes, these limit curves and model parameters provide essential information. As described by Moore[5], after introducing the concept of a "super" runner using the limit curve's performances: "the ordinary runner is one whose speed is slower, perhaps by some fixed amount over the entire age range than that of the 'super' runner." By extension, an athlete in training should exhibit higher performances compared with a nonathlete. In this way, the boundary curves appear as references to provide valuable information for coaches and sport managers in planning strategies for the athlete's longitudinal development. Comparing borderlines and parameters of national and world-class levels (Figure 2) may provide valuable information for the management of the country's infrastructure and sports policy.

The maximum performance parameter (P_{max}) quantifies the best marks for a specific sex, event, and competi-

Table 2 - Model and adjustment quality parameters quantified for the boundary curves of national and world-class athletes in four athletic jumping events.

		National				World Class			
		Long Jump	**High Jump**	**Triple Jump**	**Pole Vault**	**Long Jump**	**High Jump**	**Triple Jump**	**Pole Vault**
Female	*Pmax* (m)	6.89	1.83	14.21	4.94	7.03	2.05	15.26	5.16
	95% CI	6.86-6.93	1.82-1.84	14.13-14.27	4.87-5.08	6.98-7.11	2.04-2.06	15.15-15.42	5.02-5.41
	K (year^{-1})	0.24	0.33	0.49	0.11	0.24	0.24	0.20	0.16
	95% CI	0.22-0.27	0.23-0.44	0.42-0.59	0.09-0.14	0.15-0.34	0.18-0.32	0.14-0.27	0.11-0.21
	To (year)	7.6	5.7	11.2	4.5	6.5	6.2	4.9	4.3.
	95% CI	6.7-8.3	1.5-7.9	10.6-11.8	2.5-6.3	1.2-10.1	3.6-8.3	0.0-7.8	0.3-7.3
	95%Age	20.1	14.8	17.3	31.8	19.0	18.7	19.9	23.0
	R^2	0.96	0.87	0.93	0.97	0.84	0.93	0.90	0.86
	SD%	1.4	0.8	1.5	0.5	1.5	0.9	1.8	0.6
Male	*Pmax* (m)	8.23	2.28	17.72	5.65	8.55	2.37	17.78	5.97
	95% CI	8.20-8.27	2.27-2.29	17.61-17.83	5.63-5.69	8.47-8.70	2.35-2.38	17.20-18.00	5.93-6.10
	K (year^{-1})	0.48	0.38	0.26	0.66	0.24	0.33	0.27	0.27
	95% CI	0.43-0.54	0.36-0.42	0.24-0.29	0.60-0.72	0.14-0.29	0.26-0.40	0.17-1.03	0.15-0.36
	To (year)	11.0	10.5	8.8	13.1	6.4	8.3	7.4	8.9
	95% CI	10.6-11.5	10.1-10.7	8.2-9.3	12.8-13.3	1.1-9.1	6.4-9.5	3.3-12.1	0.4-10.9
	95%Age	17.3	18.4	20.3	17.6	18.9	17.4	18.5	20.0
	R^2	0.91	0.98	0.97	0.98	0.80	0.88	0.75	0.90
	SD%	1.2	0.9	1.3	0.7	1.4	1.0	0.7	0.9

tion level in the considered time. The comparison of maximum performance between the sexes showed that female national and world-class performances correspond to approximately 85% of male performances. This is in line with previous scientific literature data with international athletes, ranging from 81 to 85%[9,15,16]. Furthermore, the comparison between the maximum performance of national and world-class athletes revealed that Brazilian athletes present greater chances of medals in international competitions for women's long jump and pole vault and men's triple jump. On the other hand, women's high jump is an alarming case in which Brazilian athletes show a considerable distance to the international mark, which should receive the attention of the national sport managers.

The model's parameter K is a constant quantifying the rate of increase in performance and points out the fact that 14 out of 16 categories reached 95% of P_{max} at approximately 19 years. This reflects adaptations to training and to puberty, which ends between the ages of 18-20 years old. The observed difference in male and female performance evolution during puberty reveals the high levels of testosterone produced by men when compared to women[17-19]. This observation thus reinforces the contribution of maturity to performance improvement.

The various sampling processes used for national and world-class champions explain in parts the higher observed national rates of a performance increase (K) compared with world-class ones. To achieve international indexes in world-class events, the athletes underwent several selection processes. Upon being selected, they had already overcome the main learning difficulties of the jumping techniques. The higher trend observed for the national K parameters than their world-class counterparts indicates that national athletes experience accelerated growth. This could be possibly some kind of compensation for the late onset of sports training. The trend of parameter T_0 also being higher for national than world-class athletes, as already shown for K, indicates a late onset of sports training in Brazil. This leaves an unanswered question on whether the model's T_0 and the real start age of sports training are correlated. Such possibility could be tested by applying the same model to athletes from different nationalities and, probably, with different starting ages for sports training. World-class limit curves may be interpreted as the envelope curve of all national limit curves and therefore the gaps between the national and the world-class borderlines are spaces to be occupied by limit curves of other countries with better results than the nationals reported here.

Parameters K and T_0 together characterise the monotone growth of the limit performance until P_{max}. The hypothesis used to elaborate the proposed model considered K and T_0 as independent parameters. The fact that almost all groups reached 95% of P_{max} near 19 years old led to a supplementary condition, in which K and T_0 are not independent parameters but related through the linear relationship of Equation (3). This indicates that with this

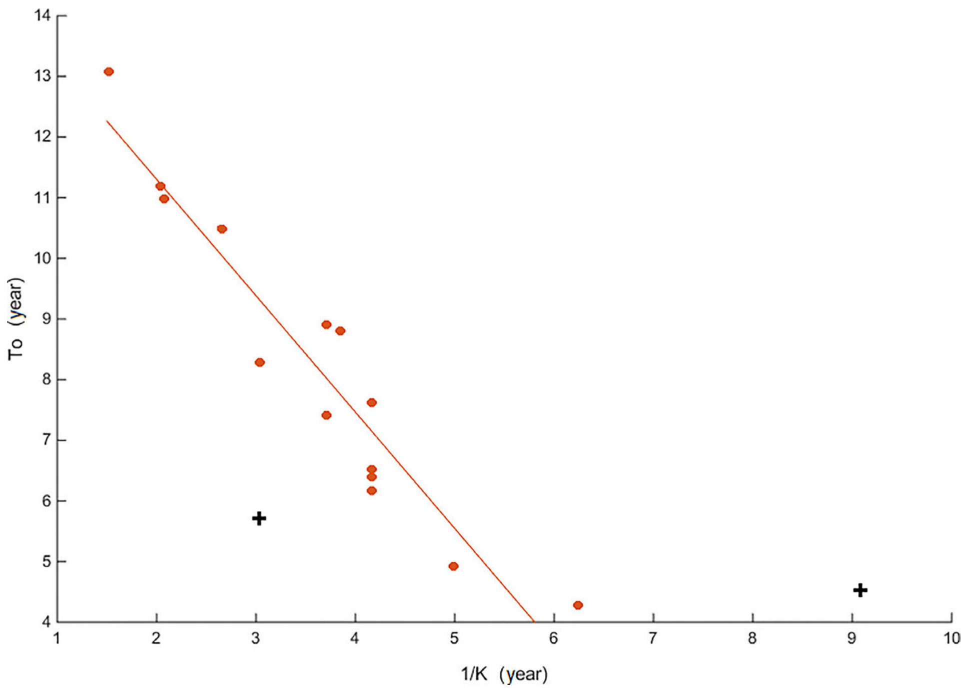

Figure 3 - Parameters To and 1/K, estimated by the phenomenological model in 16 cases studied. (+) corresponds to two outliers-women's high jump and pole vault-not used in the regression line fit.

new constraint the number of degrees of freedom of the model is reduced from three to two, and that to define a limit curve only two parameters are necessary, the value of P_{max} and the position of the studied case in the trend line.

The comparison of the borderlines shows that national performances stabilise and fail to follow the progression for world-class athletes in adulthood. This is particularly evident in the men's long jump and pole vault and the women's high and triple jumps. These patterns may reflect a national structure of early specialization seeking immediate results in early phases and adolescence. The injuries, psychological stress, and burnout may have led to athletes' discontinuing at competitions, resulting in the observed stagnation in national athletes' performance in adulthood. Coupled with this, adult athletes face several problems from a lack of financial support to continue in sports. These facts hamper the development of the sport, feeding a vicious cycle that demands reflections from various perspectives related to the country's infrastructure and sports policy which are not part of the scope of this study.

With different degrees of complexity, all the athletic jumps are preceded by horizontal running followed by one or more vertical impulses. These actions require physical strength and power, in addition to sophisticated neuromuscular and synchronization controls of recruiting motor units[20,21], but each jump requires specific technical training. We suggest that the different combinations of K, T_0 and the linear relationship described in this study could be interpreted as a manifestation of the different types of difficulties encountered in learning and training of these techniques.

Our findings should be validated by employing different approaches. Here we suggest similar research with data from other countries that may refine the interpretation of the K and T_0 parameters and their combinations, possibly relating them to the strength and power required and to the technical difficulties of the jump type. Moreover, the analysis of other countries could also advance the discussion of the correlation between T_0 and the age of beginning sports training. Also, other sports disciplines, like running as studied by Moore[5], could show if the performances improvement supports the same model and if so, with the same kind of constraint between K and T_0, as shown for the athletic jumping events.

Conclusions

The model proposed in this study demonstrates characteristics of the development of national and world-class elite athletes since the age of 14 years. The limit curves can be a useful instrument for assessing sports policy and training outcomes, and for establishing new goals related to athletic performance at athletic jumping events. The analysis of each limit curve involves also the local cultural, political, and economic context. Therefore, the analysis of the curves and the multiple factors that they represent can be an important tool for different purposes. Potentially, local training conditions, infrastructure, and sports policies offered to young athletes in different countries can affect their respective national limit curves and these effects could be detected and quantified using the model presented. World-class limit curves may be interpreted as the envelope curve of all national limit curves and therefore serve as a reference for improving local conditions.

Acknowledgments

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (CAPES) - Finance Code 001. The authors thank Espaço da Escrita - Pró-Reitoria de Pesquisa - UNICAMP - for the language services provided. We thank professor Darci Ferreira da Silva who, with his rich experience and trajectory in Brazilian athletics, contributed to data collection and to the discussion of the results found.

Reference

1. Boccia G, Moisè P, Franceschi A, Trova F, Panero D, La Torre A, et al. Career Performance Trajectories in Track and Field Jumping Events from Youth to Senior Success: The Importance of Learning and Development. PLoS One. 2017; 12(1),:e0170744. doi: 10.1371/journal.pone.0170744
2. Hollings S, Hume P, Hopkins WG. Performance progression of successful athletes: The CD performance progression tool. New Studies Athletics. 2012; 27(3), 71-79.
3. Haugen TA, Solberg PA, Foster C, Morán-Nvarro R, Breitschädel F, Hopkins WG. Peak age and performance progression in world-class track-and-field athletes. Int J Sports Physiol. 2018; 13(9), 1122-1129. doi: 10.1123/ijspp.2017-0682
4. Tønnessen E, Svendsen IS, Olsen IC, Guttormsen A, Haugen T. Performance Development in Adolescent Track and Field Athletes According to Age, Sex and Sport Discipline. Plos One; 2015; 10, e0129014.
5. Moore DH. A study of age group track and field records to relate age and running speed. Nature. 1975; 253, 264-265.
6. Berthelot G, Len S, Hellard P, Tafflet M, Guillaume M, Vollmer J, et al. Exponential growth combined with exponential decline explains lifetime performance evolution in individual and human species. Age. 2012; 34(4),1001-1009. doi: 10.1007/s11357-011-9274-9
7. Marck A, Antero J, Berthelot G, Johnson S, Sedeaud A, Leroy A, et al. Age-related upper limits in physical performances. J Gerontology. 2018; 74(5), 591-599. doi: 10.1093/gerona/gly165
8. Knechtle B, Nikolaidis PT, Di Gangi S. World single age records in running from 5 km to marathon. Front Psychol. 2018; 9, 1-18. doi: 10.3389/fpsyg.2018.02013
9. Baker AB, Tang YQ. Aging Performance for Masters Records in Athletics, Swimming, Rowing, Cycling, Triathlon, and Weightlifting. Exp Aging Res. 2010; 36(4),453-477. doi: 10.1080/0361073X.2010.507433
10. Ganse B, Ganse U, Dahl J, Degens H. Linear decrease in athletic performance during the human life span. Front Physiol. 2018; 9, 1100. doi: 10.3389/fphys.2018.01100
11. Nikolaidis PT, Zingg MA, Knechtle B. Performance trends in age-group runners from 100m to marathon-The World Championships from 1975 to 2015. Scand J Med Sci Sports. 2017; 27(12), 1588-1596. doi: 10.1111/sms.12821
12. Rittweger J, di Prampero PE, Maffulli N, Narici MV. Sprint and endurance power and ageing: an analysis of master athletic world records. Bio Sci. 2009; 276(1657), 683-689. doi: 10.1098/rspb.2008.1319
13. Radek V. Identification of peak performance age in track and field athletics. Int J Perform Anal Sport. 2014; 14(1), 238-251. doi: 10.1080/24748668.2014.11868718
14. Efron B, Tibshirani, R. Bootstrap Methods for Standard Errors, Confidence Intervals, and Other Measures of Statistical Accuracy. Statistical Sci. 1986; 1(1), 54-75.
15. Kovalchik S. Men's records and women's: are the women better already?: Moving towards a gender-neutral Olympics. Significance. 2012; 9(2), 18-23. doi: doi.org/10.1111/j.1740-9713.2012.00554.x
16. Thibault V, Guillaume M, Berthelot G, El Helou N, Schaal K, Quinquis L. Women and Men in Sport Performance: The Gender Gap has not Evolved since 1983. J Sports Sci Med. 2010; 9(2), 214-223.
17. Goswami B, Singha Roy A, Dalui R, Bandyopadhyay A. (2014). Impact of Pubertal Growth on Physical Fitness. Am J Sports Sci Med. 2014; 2(5A), 34-39. doi: 10.12691/ajssm-2-5A-8
18. Quatman CE, Ford KR, Myer GD, Hewett TE. Maturation Leads to Gender Differences in Landing Force and Vertical Jump Performance. Am J Sports Med. 2006; 34, 806-813. doi: 10.1177/0363546505281916
19. Siervogel RM, Demerath EW, Schubert C, Remsberg KE, Chumlea WC, Sun S, et al. Puberty and Body Composition. Horm Res. 60(1), 36-45. doi: 10.1159/000071224.
20. Schulz R, Curnow C. Peak Performance and Age Among Superathletes: Track and Field, Swimming, Baseball, Tennis, and Golf. J Gerontology. 1988; 43(5), P113-P120.
21. Thomas TR, Zebas CJ, Bahrke MS, Araujo J, Etheridge GL. Physiological and psychological correlates of success in track and field athletes. Br J Sports Med. 1983; 17(2), 102-109. doi: 10.1136/bjsm.17.2.102

Corresponding author

René Brenzikofer. Universidade Estadual de Campinas, Departamento de Ciências do Esporte, Faculdade de Educação Física, Av. Érico Veríssimo 701, 13083-851, Campinas, Brazil.
E-mail: brenzi@unicamp.br.

Manuscript received on July 17, 2021
Manuscript accepted on July 25, 2021