RESEARCH NOTE

Open Access

Analysis of the 10-day ultra-marathon using a predictive XG boost model



Beat Knechtle^{1,2*}, Elias Villiger², David Valero³, Lorin Braschler⁴, Katja Weiss², Rodrigo Luiz Vancini⁵, Marilia S. Andrade⁶, Volker Scheer³, Pantelis T. Nikolaidis⁷, Ivan Cuk⁹, Thomas Rosemann² and Mabliny Thuany⁸

Abstract

Objective Ultra-marathon running races are held as distance-limited or time-limited events, ranging from 6 h to 10 days. Only a few runners compete in 10-day events, and so far, we have little knowledge about the athletes' origins, performance, and event characteristics. The aim of the present study was to investigate the origin and performance of these runners and the fastest race locations. A machine learning model based on the XG Boost algorithm was built to predict running speed from the athlete's age, gender, country of origin, country where the race takes place, the type of race and the kind of running surface. The model explainability tools were then used to investigate how each independent variable would influence the predicted running speed.

Results The model rated the origin of the athlete as the most important predictor, followed by age group, running on dirt path, gender, running on asphalt, and event location. Running on dirt path led to a significant reduction of running speed, while running on asphalt showed faster running speeds compared to other surfaces. Most athletes came from USA, followed by Russia, Germany, Ukraine, the Czech Republic, and Slovakia. Most of the runners competed in USA. The fastest 10-day runners were from Finland and Israel. The fastest 10-day races were held in Greece.

Conclusions Most 10-day runners originated from USA, but the fastest runners originate from Finland and Israel. The fastest race courses were in Greece. Running on dirt paths leads to a significant reduction in running speed while running on asphalt leads to faster running speeds.

Keywords Age group, Gender, Ultra-endurance, Nationality, Origin, Performance, Machine learning

*Correspondence:

Beat Knechtle

⁸ Faculty of Sport and Physical Education, University of Belgrade, Belgrade, Serbia

⁹ Faculty of Sports, University of Porto, Porto, Portugal

Introduction

Multi-day races are running events typically held as timelimited races where athletes should complete as much distance as possible. Ultra-marathons are held from 6 h to several days, with 10-day events generally considered the longest competition duration [1-4]. A 10-day race is mainly held on flat asphalt roads or tracks where athletes have to run as many kilometers within these 10 days. Considering the difficulty level of a 10-day event, the number of participants is reduced compared to ultramarathons of shorter duration [1-4].

The low number of ultramarathoners competing in the longest time-limited race format is associated with fewer published papers investigating these races. Only a



© The Author(s) 2024. **Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by-nc-nd/4.0/.

beat.knechtle@hispeed.ch

¹ Medbase St. Gallen Am Vadianplatz, Vadianstrasse 26, 9001 St. Gallen, Switzerland

² Institute of Primary Care, University of Zurich, Zurich, Switzerland

³ Ultra Sports Science Foundation, Pierre-Benite, France

⁴ Faculty of Medicine, University of Bern, Bern, Switzerland

⁵ MoveAgeLab, Physical Education Sport Center of Federal, University of Espirito Santo, Vitoria, ES, Brazil

⁶ Physiology Department, Federal University of Sao Paulo, Sao Paulo, Brazil

⁷ School of Health and Caring Sciences, University of West Attica, Athens, Greece

few studies investigated the age of peak performance [1, 2] and the sex difference in performance [3]. Regarding the age of peak performance, a study reported a value of 44.6 years [4] while another study reported for the ten fastest women ever a value of 37 ± 4 years and for men of 48 ± 6 years [2].

Considering the origin of ultra-marathoners, we have knowledge about short events, such as 6-h [5] and 12-h races [6] where runners originated from Europe. A study showed that the fastest 100-mile ultra-marathoners come mostly from Eastern European countries such as Lithuania, Latvia, Ukraine, Finland, Russia, Hungary, Slovakia, and Israel [7]. A recent study investigating 72-h ultramarathons reported that the fastest runners originated from Ireland, Japan, and Ukraine [8].

The objectives of the study were to investigate the origin of the fastest 10-day runners and to determine the countries where the fastest 10-day events were held. We hypothesized that the fastest 10-day runners originate from Europe.

Method

Ethical approval

This study was approved by the Institutional Review Board of Kanton St. Gallen, Switzerland (EKSG 01/06/2010).

Data set and data preparation Data download

Race data was downloaded from the website of DUV (Deutsche Ultramarathon Vereinigung) (https://stati stik.d-u-v.org). Each race record included the athlete's first and last name, age group, gender, country of origin, race location and year, race performance in distance (km) and average running speed (km/h). We added the type of the race (road or track running) and the running surface (gravel, paving, grass, concrete, asphalt, and combinations).

Country rankings by number of race records and unique runners

The data set is aggregated by the values in the *athlete country* column and then sorted by number of records to rank the athletes' countries by number of race records. To rank the countries holding the events by the number of race records, the data set is aggregated by the values in the *event country* column and then sorted by number of records. Running speed descriptive statistics and unique runners are calculated for each country. The mean running speed is color-coded, with darker colors corresponding to higher values (faster running speeds). The first column in the ranking tables is the index to interpret the PDP charts (Partial dependence plots).

XG boost regression model

The algorithm used is the XG Boost (eXtreme Gradient Boosting), trained with the full sample. The 10-day sample used to build, evaluate, and interpret the XG Boost regression model consists of 958 race records from 452 unique runners from 46 countries who participated in races held in 6 countries between 1991 and 2022. The following variables are used as predictors, or inputs to the model: Athlete_gender_ID, Age_group_ID, Athlete_country_ID, Event_country_ID. The binary indicators of running surface (RS): RS_asphalt, RS_concrete, RS_dirt_path, RS_grass, RS_gravel, RS_paving, RS track. The predicted variable, or algorithm output is the Race (running) speed (km/h) variable. A holdout evaluation strategy was used to train and evaluate the model, iteratively training and evaluating different instances with different test splits and different numbers of estimators/learn rates. Two evaluation metrics, MAE (mean absolute error) and r^2 , are calculated with the model SHAP-based (SHapley Additive exPlanations) relative features importances. PDP and prediction distribution plots are computed and compared to the full sample descriptive charts. The optimal model parameters and accuracy scores were: 200 estimators (learners or trees); learning rate of 0.5; r^2 score of 0.65 (in-sample test); and MAE of 0.37 km/h.

Numerical encoding of categorical variables

Before the XG Boost model could be trained, the predictor values had to be converted (encoded) into numerical data. The *Athlete gender* variable is encoded as female=0 and male=1. The *Age group* variable is numerically encoded in 5-year groups. The *Athlete country* and *Event country* variables are encoded based on their position in the rankings' tables. The *run surface* variable is one-hot encoded, giving place to a set of 7 new binary variables that indicate if the race takes place in that surface (1) or otherwise (0).

Baseline model with OLS MLR

Here we build a Multivariable Linear Predictor (MLR) based on Ordinary Least Squares (OLS) to predict the average race speed from the available predictors.

Model training and evaluation strategy

A holdout evaluation strategy is used to tune the model by iteratively training and evaluating different models with different test splits and different numbers of estimators/learn rates. The results of the simulation achieved the best r^2 scores of 0.648.

Table 1 Athlete country ranking

	Athlete country	Race speed (km/h)		Race records	Unique runners		
		mean	std	min	max		
27	BLR	3.720	0.743	3.039	4.495	4	3
28	SWE	2.731	0.676	2.141	3.478	4	1
29	SLO	3.316	0.152	3.152	3.507	4	3
30	FIN	5.207	0.619	4.493	5.586	3	2
31	NEP	2.828	0.795	2.099	3.675	3	1
32	JPN	3.787	0.515	3.429	4.377	3	1
33	TPE	4.054	0.562	3.413	4.458	3	2
34	ISR	4.796	0.232	4.641	5.063	3	2
35	MDA	3.710	0.254	3.420	3.889	3	1
36	ARG	3.676	0.131	3.583	3.769	2	2
37	DEN	4.426	0.313	4.204	4.647	2	2
38	POR	1.881	0.346	1.636	2.126	2	2
39	GRE	3.196	0.395	2.917	3.475	2	2
40	IRL	4.439	0.379	4.171	4.707	2	1
41	CRO	2.960	-	-	-	1	1
42	PHI	0.211	-	-	-	1	1
43	MKD	3.708	-	-	-	1	1
44	MAR	3.373	-	-	-	1	1
45	HKG	3.158	-	-	-	1	1

Optimal model evaluation metrics and features importance

The model is finally rebuilt with n_estimators = 200 and learn_rate = 0.5 and trained and tested over the full sample, obtaining an accuracy value of R^2 = 0.65, which indicates the model can explain 65% of the variability of the target (race speed) within this dataset. All computation and analysis were performed using a Jupyter notebook (Google Colab) and Python and associated libraries (pandas, numpy, xgboost, pdp-box, sklearn, matplotlib, and sns).

Event country	Race speed (km/h)					Race records	Unique runners
		mean	std	min	max		
0	USA	3.224	0.929	0.211	6.042	838	372
1	RSA	2.544	0.872	0.793	4.684	49	43
2	ITA	3.066	0.840	1.145	4.511	33	21
3	BUL	3.566	0.654	2.522	4.959	17	17
4	CHN	3.509	1.043	1.493	5.000	12	12
5	GRE	3.773	0.595	2.917	4.733	9	9

Table 2 Event country ranking

Impact of the predictors on XG Boost regressor race speed predictions



Fig. 1 SHAP aggregated values chart for XG Boost model

Results

Table 1 summarizes the race records by the countries of origin of the athletes. Most athletes came from USA, Russia, Germany, Ukraine, the Czech Republic, and Slovakia. The fastest runners were from Finland.

Table 2 summarizes the events. Most of the runners competed in USA. The fastest running speeds were achieved in Greece.

Multivariable linear predictor (MLR) based on ordinary least squares (OLS)

The model obtains $r^2=0.210$ where all predictors are statistically significant except *Gender_ID*, *RS_concrete, and Event_country_ID*. The simple MLR model can only model linear relationships, so that is how even the coefficients do not align with the most sophisticated ML (XG Boost+SHAP+PDP) analysis.

Number of unique grid points: 2





Number of unique grid points: 13



Fig. 3 Partial dependence plots (PDP) for age group

PDP for feature Athlete_country_ID

Number of unique grid points: 46





Number of unique grid points: 6



Fig. 5 Partial dependence plots (PDP) for the country where the race was held

PDP for feature RS_asphalt

Number of unique grid points: 2





Number of unique grid points: 2



Fig. 7 Partial dependence plots (PDP) for running surface concrete

PDP for feature **RS_dirt_path**

Number of unique grid points: 2







Number of unique grid points: 2



Fig. 9 Partial dependence plots (PDP) for running surface grass

Number of unique grid points: 2





Number of unique grid points: 2



Fig. 11 Partial dependence plots (PDP) for running surface paving

PDP for feature **RS_track**

Number of unique grid points: 2



Fig. 12 Partial dependence plots (PDP) for running surface track

SHAP aggregated values chart for XG Boost model

Athlete_country_ID is the most important feature. This variable is encoded according to the country position in the ranking. Age_group_ID makes for a more interpretable chart, with red dots (higher ages) on the left side, hence reducing running speed. Similarly, Gender_ID has only two values. The SHAP chart shows low values (blue dots, female race records) accumulate on the left, meaning a reduction of the race speed. RD_dirt_path and RS_asphalt are both among the top features by importance, and with a separation of the dots. In the first case, red dots (presence of this running surface in the race) see a reduction of running speed. The interpretation for the asphalt flag is right the opposite (Fig. 1).

Model:	OLS	Adj. R-squared:	0.203	
Dependent variable:	Running speed (km/h)	AIC:	2377.4291	
		BIC:	2426.0775	
No. Observations:	958	Log-Likelihood:	- 1178.7	

Model:	OLS	Adj. R-squared:	0.203
Df model:	9	F-statistic:	28.04
Df residuals:	948	Prob (F-statistic):	2.27e-43
R-squared:	0.210	Scale:	0.69309

	Coef	Std.Err	t	P> t	[0.025	0.975]
const	2.5113	0.1128	22.2574	0.0000	2.2898	2.7327
Gen- der_ID	0.0853	0.0569	1.4989	0.1342	- 0.0264	0.1969
Age_ group_ID	- 0.0127	0.0023	- 5.5512	0.0000	- 0.0172	- 0.0082
Athlete_ coun- try_ID	0.0086	0.0034	2.5458	0.0111	0.0020	0.0152
Event_ coun- try_ID	0.0294	0.0348	0.8469	0.3973	- 0.0388	0.0977
RS_ asphalt	1.2674	0.0735	17.2548	0.0000	1.1233	1.4116
RS_con- crete	- 0.1584	0.2299	- 0.6892	0.4909	- 0.6096	0.2927

Model interpretability charts for feature: Gender



Fig. 13 Prediction distributions and gender-target plots

	Coef	Std.Err	t	P> t	[0.025	0.975]
RS_dirt_ path	- 1.0230	0.0975	- 10.4971	0.0000	- 1.2143	-0.8318
RS_grass	0.5096	0.1748	2.9147	0.0036	0.1665	0.8527
RS_gravel	0.4702	0.1743	2.6977	0.0071	0.1282	0.8123
RS_paving	0.3118	0.1206	2.5844	0.0099	0.0750	0.5486
RS_track	0.4225	0.1606	2.6311	0.0086	0.1074	0.7376

Partial dependence plots (PDP)

The model output is ~ 0.2 km/h higher for males than females (Fig. 2). The highest model output is given to

runners in age group 45–49 years (Fig. 3). The results by athlete country reached their peak at ID 30 (Finland), followed by Israel (ID 34) (Fig. 4). The event country PDP is flat, with a 0.1–0.2 km/h difference between the average model output. This is in line with the low importance rating of the feature (Fig. 5). Figures 6, 7, 8, 9, 10, 11, 12 present the PDP for the running surfaces. Running on asphalt is faster than running on any other surface.

Prediction distributions and target plots

The difference between the predictions of men and women is ~ 0.11 km/h (Fig. 13). The 45–49-year age



Model interpretability charts for feature: Age group

group leads (Fig. 14). Finland and Israel are the fastest countries of origin (Fig. 15) and Greece holding the fastest races (Fig. 16). Figures 17, 18, 19, 20, 21, 22, 23 show the prediction distributions and target plots for running surfaces. Running on asphalt is faster than running on any other surface.

Discussion

Origin of the fastest 10-day runners

The model assigned the highest importance to the athlete's origin as the primary predictor. Age group emerged as the second most influential factor, followed by gender and the event's location. This order of importance suggests that the geographical background of the athlete plays a crucial role in shaping performance. Most athletes came from USA, followed by runners from Eastern Europe (Russia, Germany, Ukraine, the Czech Republic, and Slovakia). The high number of US-American athletes is explained by the 'Sri Chinmoy 10 Day Race' held since 1996, accumulating a participant count exceeding 700 finishers over the years. (https:// us.srichinmoyraces.org/events/6-10-day-race). This enduring history of the event highlights the consistent participation of athletes from the USA. Some of the



abovementioned countries had a tradition of high-level ultra-marathon runners where Russian runners dominate the 'Comrades Marathon' [9].

Finland and Israel as dominating nations

The fastest runners were from Finland. One of them is Pekka (Asprihanal) Aalto, who had a personal best performance of 1340 km in 10 days (https://3100.srich inmoyraces.org/ashprihanal-aalto). Finland has a large ultra-marathon scene with the 'Kauhajoki Ultra Running Festival' (http://karhumaraton.fi/kurf). In contrast, Israel has short ultra-marathon such as the 'Ultramarathon Sovev Emek' as Israel's longest ultra race (https:// sovev-emek.org/), the 'Spartanion' (https://spartanion. com/) or the 'Dead Sea Marathon Israel' (https://deads ea.run/en/).

The fastest races

The fastest running speeds were achieved in Greece. In the 'Athens International Ultramarathon Festival' in Athens, Greece, many different race formats have been offered since 2005 (www.dayrunners.gr/). A 10-day



Model interpretability charts for feature: Event country

Fig. 16 Prediction distributions and target plots for the country where the events took place

split was recorded at '1000 Miles Athens Int. Ultramarathon Festival'. Why are most ultramarathon runners from Europe? We think it is possible to draw a parallel with the same factors with the Kenyan, Ethiopian, and Jamaican runners [10]. The prevalence of ultramarathoners originating from Europe can be attributed to several factors [11] such the tradition and history of long-distance running in European countries [12, 13]. The continent hosts numerous well-established races, providing ample opportunities for individuals to engage in ultrarunning [14]. Cultural and social factors, such as a strong emphasis on health and wellness, may also play a role [15, 16]. The European lifestyle, with its focus on outdoor activities and a holistic approach to well-being, aligns well with the demands and aspirations of ultramarathon enthusiasts [17].

Model interpretability charts for feature: RS_asphalt



Fig. 17 Prediction distributions and target plots for running surface asphalt

Men were faster than women

Men ran 0.11 km/h faster than women which is wellknown in ultra-running [18]. The gap decreases with increasing race distance/duration [18] and age [19]. Women could reduce the gap to men for most timed ultra-marathons and for those age groups where they had a high participation [3]. The physiological differences between men and women can contribute to the performance gap. Possible reasons are differences in muscle mass [20] and muscle strength [21], running stride [22], aerobic capacity [23, 24], metabolism [26, 26], hormonal metabolism [27–29], fatigue resistance [25], and training strategies [30, 31].

The age of peak running performance

The fastest running speeds were achieved in age group 45–49 years. The 10-day race format is the longest race format for time-limited ultra-marathons, and it has been shown that the age of maximum ultra-marathon performance increased with increasing race duration in time-limited races from 6 h to 10 days [4]. The observed phenomenon can be explained by a combination of





Fig. 18 Prediction distributions and target plots for running surface concrete

different factors such as experience [32] and training [33], aerobic capacity [34, 35], muscle efficiency [36], running technique [37, 38], mental toughness [39, 40], experience [4], recovery [41], injury prevention [41], optimal body composition [42] and physiological adaptations [43–45].

The aspect of running surface

These races are all held on a flat terrain, some races are held across two different surfaces (asphalt and dirt path). Asphalt seems to be the fastest surface, where the other surfaces show a reduction in running speed. Little is known regarding the impact of running surface on running performance. Ferro-Sánchez et al. investigated the impact of different running surfaces (grass, synthetic track, and concrete) and found that greater impacts were produced on concrete compared to synthetic track and grass [46]. Tessutti et al. analyzed the influence of running on asphalt, concrete, natural grass, and rubber on in-shoe pressure patterns and found that running on natural grass attenuates in-shoe plantar pressures [47]. Wang et al. analyzed plantar load data during running on concrete, synthetic rubber, and grass



Model interpretability charts for feature: RS_dirt_path

3.6

3.2





Fig. 20 Prediction distributions and target plots for running surface grass

Page 19 of 23



Fig. 21 Prediction distributions and target plots for running surface gravel



Model interpretability charts for feature: RS_track



Fig. 23 Prediction distributions and target plots for running surface track

surfaces and showed that different surfaces affected the plantar loads differently while running [48]. Ultramarathoners would profit from selecting ultramarathon running races with asphalt considering a faster running speed.

Conclusion

Finland and Israel as countries producing the fastest runners in the 10-day format adds a valuable dimension to our understanding. The revelation that Greece hosts the fastest race courses contributes practical information to professionals, including athletes, coaches, and race directors, enabling them to set optimal performance goals based on the event country. Running on dirt path led to a reduction of running speed, while running on asphalt showed faster running speeds compared to other surfaces.

Abbreviations

DUV	Deutsche ultramarathon vereinigung
MAE	Mean absolute error
MLR	Multivariable linear predictor
OLS	Ordinary least squares
PDP	Partial dependence plots
SHAP	SHapley Additive exPlanations
XG Boost algorithm	EXtreme gradient boosting

Acknowledgements

Not applicable.

Author contributions

BK and MT drafted the manuscript, EV obtained the data, DV performed the statistical analysis and prepared methods and results, LB, KW, RLV, MSA, VS, PTN, TR and IC helped draft the final version. All authors read and approved the final manuscript.

Funding

No funding.

Availability of data and materials

For this study, we have included the official results from the official website (https://statistik.d-u-v.org/geteventlist.php). The data sets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

This study was approved by the Institutional Review Board of Kanton St. Gallen, Switzerland, with a waiver of the requirement for informed consent of the participants, as the study involved the analysis of publicly available data (EKSG 01/06/2010). The study was carried out according to recognized ethical standards according to the Declaration of Helsinki adopted in 1964 and revised in 2013.

Consent for publication

Not applicable.

Competing interests

Beat Knechtle, Elias Villiger, David Valero, Lorin Braschler, Katja Weiss, Rodrigo Luiz Vancini, Marilia S. Andrade, Volker Scheer, Pantelis T. Nikolaidis, Ivan Cuk, Thomas Rosemann, and Mabliny Thuany declare no competing interests

Received: 5 March 2024 Accepted: 3 December 2024 Published online: 19 December 2024

References

- Nikolaidis PT, Knechtle B. Age of peak performance in 50-km ultramarathoners—is it older than in marathoners? Open Access J Sports Med. 2018;1(9):37–45. https://doi.org/10.2147/OAJSM.S154816.
- Rüst CA, Zingg MA, Rosemann T, Knechtle B. Will the age of peak ultra-marathon performance increase with increasing race duration? BMC Sports Sci Med Rehabil. 2014;27(6):36. https://doi.org/10.1186/ 2052-1847-6-36.
- Knechtle B, Valeri F, Nikolaidis PT, Zingg MA, Rosemann T, Rüst CA. Do women reduce the gap to men in ultra-marathon running? Springerplus. 2016;5(1):672. https://doi.org/10.1186/s40064-016-2326-y.
- Knechtle B, Valeri F, Zingg MA, Rosemann T, Rüst CA. What is the age for the fastest ultra-marathon performance in time-limited races from 6 h to 10 days? Age. 2014;36(5):9715. https://doi.org/10.1007/ s11357-014-9715-3.
- Ehrensperger L, Knechtle B, Rüst CA, Rosemann T. Participation and performance trends in 6-hour ultra-marathoners: a retrospective data analysis of worldwide participation from 1991–2010. J Hum Sport Exerc. 2013;8(4):905–24.
- Sehovic E, Knechtle B, Rüst CA, Rosemann T. 12-hour ultra-marathons: increasing worldwide participation and dominance of Europeans. J Hum Sport Exerc. 2013;8(4):932–53.
- Knechtle B, Weiss K, Valero D, Villiger E, Nikolaidis PT, Andrade MS, Scheer V, Cuk I, Gajda R, Thuany M. Using machine learning to determine the nationalities of the fastest 100-mile ultra-marathoners and identify top racing events. PLoS ONE. 2024;19(8):e0303960. https://doi. org/10.1371/journal.pone.0303960.
- Knechtle B, Villiger E, Weiss K, Valero D, Gajda R, Scheer V, de Lira CAB, Braschler L, Nikolaidis PT, Vancini RL, Cuk I, Rosemann T, Thuany T. Analysis of the 72-h ultramarathon using a predictive XG boost model. Sport Sci Health. 2024. https://doi.org/10.1007/s11332-024-01243-3.

- Nikolaidis PT, Knechtle B, Vancini R, Gomes M, Sousa C. Participation and performance in the oldest ultramarathon-comrades marathon 1921–2019. Int J Sports Med. 2021;42(7):638–44. https://doi.org/10. 1055/a-1303-4255.
- 10 Vitti A, Nikolaidis PT, Villiger E, Onywera V, Knechtle B. The, "New York City Marathon": participation and performance trends of 1.2M runners during half-century. Res Sports Med. 2020;28(1):121–37. https://doi. org/10.1080/15438627.2019.1586705.
- Shoak MA, Knechtle B, Rüst CA, Lepers R, Rosemann T. European dominance in multistage ultramarathons: an analysis of finisher rate and performance trends from 1992 to 2010. Open Access J Sports Med. 2013;11(4):9–18. https://doi.org/10.2147/OAJSM.S39619.
- 12. Scheerder J, Breedveld K, Borgers J. Who is doing a run with the running boom? In: Scheerder J, Breedveld K, Borgers J, editors. Running across Europe: the rise and size of one of the largest sport markets. London: Palgrave Macmillan; 2015. p. 1–27.
- 13 Scheerder J, Breedveld K, Borgers J. Running across Europe—the rise and size of one of the largest sport markets. New York: Palgrave Macmillan; 2015.
- Knechtle B, Gomes M, Scheer V, Gajda R, Nikolaidis PT, Hill L, Rosemann T, Sousa CV. From athens to sparta-37 years of spartathlon. Int J Environ Res Public Health. 2021;18(9):4914. https://doi.org/10.3390/ijerph18094914.
- Stempień JR, Dąbkowska-Dworniak M, Stańczyk M, Tkaczyk M, Przybylski B. Particular dimensions of the social impact of leisure running: study of Poland. Sustainability. 2022;14(18):11185. https://doi.org/10.3390/su141 811185.
- Rozmiarek M, Malchrowicz-Mośko E, León-Guereño P, Tapia-Serrano MÁ, Kwiatkowski G. Motivational differences between 5k runners, marathoners and ultramarathoners in Poland. Sustainability. 2021;13(12):6980. https://doi.org/10.3390/su13126980.
- Andkjær S, Klein-Wengel TT, Ishøi A, Bjørk PC. Being and doing in the outdoors brings something extral Evaluating the danish healthy in nature project. Int J Qual Stud Health Well-Being. 2021;16(1):1983947. https:// doi.org/10.1080/17482631.2021.1983947.
- Le Mat F, Géry M, Besson T, Ferdynus C, Bouscaren N, Millet GY. Running endurance in women compared to men: retrospective analysis of matched real-world big data. Sports Med. 2023;53(4):917–26. https://doi. org/10.1007/s40279-023-01813-4.
- Knechtle B, Witthöft A, Valero D, Thuany M, Nikolaidis PT, Scheer V, Forte P, Weiss K. Elderly female ultra-marathoners reduced the gap to male ultramarathoners in Swiss running races. Sci Rep. 2023;13(1):12521. https:// doi.org/10.1038/s41598-023-39690-6.
- Bartolomei S, Grillone G, Di Michele R, Cortesi M. A comparison between male and female athletes in relative strength and power performances. J Funct Morphol Kinesiol. 2021;6(1):17. https://doi.org/10.3390/jfmk6 010017.
- Herda AA, Nabavizadeh O. Gender comparison of muscle quality and relationship with functional ability. Ageing Int. 2024;49:235–48. https:// doi.org/10.1007/s12126-023-09540-x.
- Krzysztofik M, Wilk M, Wojdała G, Gołaś A. Maximizing muscle hypertrophy: a systematic review of advanced resistance training techniques and methods. Int J Environ Res Public Health. 2019;16(24):4897. https:// doi.org/10.3390/ijerph16244897.
- Tiller NB, Wheatley-Guy CM, Fermoyle CC, Robach P, Ziegler B, Gavet A, Schwartz JC, Taylor BJ, Constantini K, Murdock R, Johnson BD, Stewart GM. Sex-specific physiological responses to ultramarathon. Med Sci Sports Exerc. 2022;54(10):1647–56. https://doi.org/10.1249/MSS.00000 0000002962.
- Cheng JC, Chiu CY, Su TJ. Training and evaluation of human cardiorespiratory endurance based on a fuzzy algorithm. Int J Environ Res Public Health. 2019;16(13):2390. https://doi.org/10.3390/ijerph16132390.
- Berger NJA, Best R, Best AW, Lane AM, Millet GY, Barwood M, Marcora S, Wilson P, Bearden S. Limits of ultra: towards an interdisciplinary understanding of ultra-endurance running performance. Sports Med. 2024;54(1):73–93. https://doi.org/10.1007/s40279-023-01936-8.
- Hausswirth C, Lehénaff D. Physiological demands of running during long distance runs and triathlons. Sports Med. 2001;31(9):679–89. https://doi.org/10.2165/00007256-200131090-00004.
- van Anders SM, Steiger J, Goldey KL. Effects of gendered behavior on testosterone in women and men. Proc Natl Acad Sci USA. 2015;112(45):13805–10. https://doi.org/10.1073/pnas.1509591112.

- Tiller NB, Elliott-Sale KJ, Knechtle B, Wilson PB, Roberts JD, Millet GY. Do sex differences in physiology confer a female advantage in ultraendurance sport? Sports Med. 2021;51(5):895–915. https://doi.org/10. 1007/s40279-020-01417-2.
- Tyagi V, Scordo M, Yoon RS, Liporace FA, Greene LW. Revisiting the role of testosterone: are we missing something? Rev Urol. 2017;19(1):16–24. https://doi.org/10.3909/riu0716.
- Knechtle B, Nikolaidis PT. Physiology and pathophysiology in ultramarathon running. Front Physiol. 2018;1(9):634. https://doi.org/10. 3389/fphys.2018.00634.
- Röthlin P, Wyler M, Müller B, Zenger N, Kellenberger K, Wehrlin JP, Birrer D, Lorenzetti S, Trösch S. Body and mind? Exploring physiological and psychological factors to explain endurance performance in cycling. Eur J Sport Sci. 2023;23(1):101–8. https://doi.org/10.1080/17461391.2021. 2018049.
- Nikolaidis PT, Alvero-Cruz JR, Villiger E, Rosemann T, Knechtle B. The age-related performance decline in marathon running: the paradigm of the berlin marathon. Int J Environ Res Public Health. 2019;16(11):2022. https://doi.org/10.3390/ijerph16112022.
- Hughes DC, Ellefsen S, Baar K. Adaptations to endurance and strength training. Cold Spring Harb Perspect Med. 2018;8(6):a029769. https://doi. org/10.1101/cshperspect.a029769.
- 34 Milanović Z, Pantelić S, Trajković N, Sporiš G, Kostić R, James N. Agerelated decrease in physical activity and functional fitness among elderly men and women. Clin Interv Aging. 2013;8:549–56. https://doi.org/10. 2147/CIA.S44112.
- 35 Knechtle B, Nikolaidis PT. The age of the best ultramarathon performance—the case of the "comrades marathon." Res Sports Med. 2017;25(2):132–43. https://doi.org/10.1080/15438627.2017.1282357.
- Leslie E, Luna V, Gibson AL. Older adult aerobic capacity, muscular strength, fitness and body composition after 20+ years of exercise training: a systematic review and meta-analysis. Int J Exerc Sci. 2023;16(3):620–37.
- 37 Klein M, Patterson C. Changes in running biomechanics in master runners over age 50: a systematic review. Sports Biomech. 2023. https://doi.org/ 10.1080/14763141.2023.2226139.
- van Oeveren BT, de Ruiter CJ, Beek PJ, van Dieën JH. The biomechanics of running and running styles: a synthesis. Sports Biomech. 2024;23(4):516– 54. https://doi.org/10.1080/14763141.2021.1873411.
- 39 Gameiro N, Rodrigues F, Antunes R, Matos R, Amaro N, Jacinto M, Monteiro D. Mental toughness and resilience in trail runner's performance. Percept Mot Skills. 2023;130(3):1202–20. https://doi.org/10.1177/00315 125231165819.
- Goddard K, Roberts CM, Anderson L, Woodford L, Byron-Daniel J. Mental toughness and associated personality characteristics of marathon des sables athletes. Front Psychol. 2019;4(10):2259. https://doi.org/10.3389/ fpsyg.2019.02259.
- Vincent HK, Brownstein M, Vincent KR. Injury prevention, safe training techniques, rehabilitation, and return to sport in trail runners. Arthrosc Sports Med Rehabil. 2022;4(1):e151–62. https://doi.org/10.1016/j.asmr. 2021.09.032.
- Kornadt AE, Kessler EM, Wurm S, Bowen CE, Gabrian M, Klusmann V. Views on ageing: a lifespan perspective. Eur J Ageing. 2019;17(4):387–401. https://doi.org/10.1007/s10433-019-00535-9.
- 43 Ilardo M, Nielsen R. Human adaptation to extreme environmental conditions. Curr Opin Genet Dev. 2018;53:77–82. https://doi.org/10.1016/j.gde. 2018.07.003.
- Berthelot G, Len S, Hellard P, Tafflet M, Guillaume M, Vollmer JC, Gager B, Quinquis L, Marc A, Toussaint JF. Exponential growth combined with exponential decline explains lifetime performance evolution in individual and human species. Age. 2012;34(4):1001–9. https://doi.org/10.1007/ s11357-011-9274-9.
- Marck A, Antero J, Berthelot G, Johnson S, Sedeaud A, Leroy A, Marc A, Spedding M, Di Meglio JM, Toussaint JF. Age-related upper limits in physical performances. J Gerontol A Biol Sci Med Sci. 2019;74(5):591–9. https:// doi.org/10.1093/gerona/gly165.
- Ferro-Sánchez A, Martín-Castellanos A, de la Rubia A, García-Aliaga A, Hontoria-Galán M, Marquina M. An analysis of running impact on different surfaces for injury prevention. Int J Environ Res Public Health. 2023;20(14):6405. https://doi.org/10.3390/ijerph20146405.

- 47. Tessutti V, Ribeiro AP, Trombini-Souza F, Sacco IC. Attenuation of foot pressure during running on four different surfaces: asphalt, concrete, rubber, and natural grass. J Sports Sci. 2012;30(14):1545–50. https://doi.org/10.
- 1080/02640414.2012.713975.
 Wang L, Hong Y, Li JX, Zhou JH. Comparison of plantar loads during running on different overground surfaces. Res Sports Med. 2012;20(2):75–85. https://doi.org/10.1080/15438627.2012.660816.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.