Scaling approach to the physiology of distance running

SCIENCE: Performance characteristics of 1500m and 10.000m specialists. A new model for human running performance by Guillaume Adam & Thorsten Emig

Introduction

Models to predict performances in running can be useful for both racing and training. It has been almost hundred years since the first systematic study of the connection between physiological principles and world record running performances was performed by Nobel prize winner Archibald Hill (1925). He proposed a mathematical model, based on metabolic energy considerations, for the maximal power output during a race. His so- called running curve predicts that the maximal power output first decreases rapidly with race time but then remains constant. This implies the existence of maximal speed that can be sustained for any duration. Variations of Hill's model have been proposed to predict performances. However, the existence of a maximal speed that is sustainable for an arbitrarily long race contradicts running records. In fact, existing models appear to be unable to explain a fundamental observation that has been made already by Hill: The average running speed during a race keeps decreasing with the duration of the race but rather slowly, namely according to a logarithmic time scale, see Fig. 1.

For distances raced below VO2max speed, this means that the difference between racing speed and speed at VO2max increases two times when the race duration is squared. For example, if the speed at VO2max is 400m/ min, and the average speed during a 10min race is 370m/min, then the speed difference is 30m/min, and the runner can sustain a speed of 340m/min for 102 min = 100min.

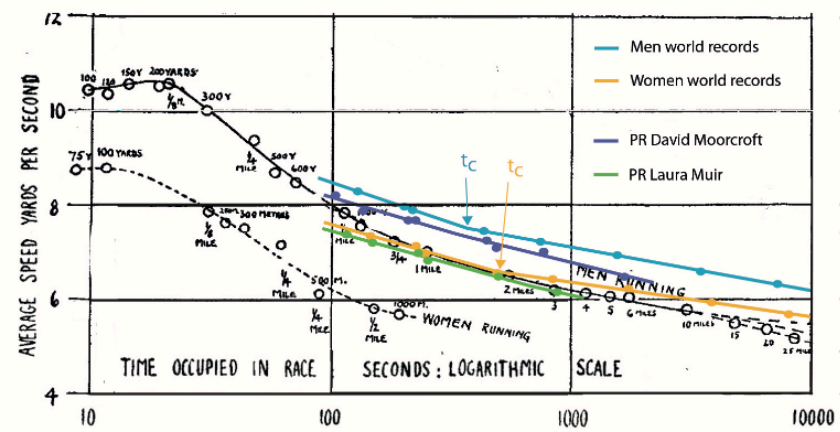


Fig.1: Relation between race times and speeds: Modified version of original graph of world records from A.V. Hill, The physiological basis of athletic records, The Lancet (1925), together with current world records and the personal records of David Moorcroft and Laura Muir.

This observation has been employed by Peronnet and Thibault in 1989 to deduce physiological characteristics from running records and to predict running performances with high accuracy. They introduced an endurance index for long distances that accounts for fatigue effects that are not related to VO2max, and not accounted for by an effective VO2max like the VDOT index in Daniels' popular running formula. The endurance index measures the amount of the above mentioned speed difference to the speed at VO2max. Given these observations, one might ask what are the important physiological parameters that determine running performances over a wide range of distances. To answer this question, we recently developed a theoretical model from basic principles of metabolic power generation and utilisation. An important observation that is essential for the construction of our model is that running economy (the linear relation between power output and running speed) usually becomes worse with the duration of a running event.

The detailed reasons for this observation are unknown. To our knowledge, our model is the first to explain the observed logarithmic relation between record running speeds and times. Not only world records but also the nowadays available large databases of race results, like PowerOf10 in the UK, helped validating our mathematical model.

	1500m Men	1500m Women	10K Men	10K Women
speed $v_{6\,min}$ [m/min]	380.9	334.3	374.5	325.5
time t_c [min]	7.9	8.9	6.6	8.5
relative aerobic energy for t_c [%]	89.4	89.4	91.0	91.2
time $t_{90\,\%}$ [min]	32.2	38.2	35.8	54.6
AEI	3.91	4.11	5.43	6.27
time $t_{110\,\%}$ [min]	3.3	3.8	2.2	2.7
ANEI	0.42	0.41	0.35	0.34
average error for race times[%]	0.74	0.77	0.77	0.76

Table 1: Model predictions for physiological characteristics (average values for top 450 runners in each of the four groups). Last line: Average deviation (relative error in %) between model and actual PRs.

Model for running performance and its applications

The idea behind our model is to find a minimal description of running performances that contains sufficient information about different physiological aspects as maximal aerobic power or endurance but not more parameters than necessary to reproduce and predict performances with high accuracy.

Contrary to many other models, we do not fix a priori any parameters but determine them individually from best performances. To describe running performance, one needs to know the power that a runner requires to run at a given speed (known as economy) and the maximal average power that the runner can sustain over a given duration. The new insight from our research is that the dependence of the maximally sustainable power on duration can be computed from the upward shift of the power output that compensates the decline of running economy over time. The result of our computation leads precisely to the relation between speed and logarithmic time depicted in Fig. 1 for the 1925 world records (according to Hill) and the current world records.

Interestingly, our study predicts a certain race duration t_c where the slope of linear relation between speed and logarithmic time changes, see Fig. 1. The time and speed at this point can be associated with maximal aerobic power or oxygen uptake. When we determine the parameters of our model from current world records and then deduce the record times from those model parameters we find a prediction error of less than 1%. After this validation for world records, we decided to apply the model to hundreds of individual runners. In British running, both David Moorcroft and Laura Muir are probably two of the best examples for consistent performances over a large range of events, from 800m to 5000m. Their personal records are shown in Fig. 1. Due to their specialisation to middle distances only, the change of slope at t_c is less pronounced. Often it is not possible to have fully consistent data for 800 meter specialists who do not have sufficiently many results on longer distances. Also, performances should be accomplished at a similar running level, typically within one or two seasons for young pro-runners as their running performance improves quickly.

Physiological parameters: velocity at VO2max, time at VO2max, aerobic endurance, and anaerobic endurance

From our model every runner can obtain four physiological indices that are computed from the performances on their raced distances: (1) the time t_c at which the graph in Fig.1 changes slope, typically the time over which maximal aerobic power (VO2max) can be sustained, (2) the average speed that the runner achieves during a race of duration t_c, (3) the aerobic endurance index (AEI) that is determined by the slope of the graph above t_c measuring the long distance endurance, and (4) the anaerobic endurance index (ANEI) obtained from the slope below t_c quantifying the short distance endurance. The first two indices could be obtained in a lab test, with the potential problems of fluctuating treadmill speed due to breaking forces and a lack of "real world" conditions. The two endurance indices can be obtained only from race results or time trials. The practical meaning of the AEI is that a runner can sustain 90% of maximal aerobic power for a duration of t_c multiplied by AEI. Similarly, 110% of maximal aerobic power can be kept up for a shorter duration of t_c multiplied by ANEI. These indices allow to compare runner's various factors that determine performance. The faster you are, the higher the velocity at VO2max. Nevertheless, t_c, AEI, and ANEI can be the same for runners of completely different levels, and they depend on the distance specialisation of a runner.

Databases of running performances: Effect of specialised training

Nowadays, large and detailed open access databases with athletic performances are available online. For example, in the British database PowerOf10 or in the French Athletics Federation database, all race performances for a given runner are available. This makes it possible to validate mathematical models without using sometimes artificial result from lab testings. Nevertheless, data quality still can have some impact. For example, race performances do not always reflect the full potential of an athlete if it was in a tactical race or if the runner was not in a peak shape. Therefore we only considered personal records (PRs) and we neglected performances that were clearly inconsistent with other PRs of the runner (e.g. average speed slower on a shorter distance). In order to test our model and extract typical physiological indices for runners specialised on different distances, we analysed PRs of British athletes from the database PowerOf10. We selected four groups, each containing 450 runners, composed of female and male

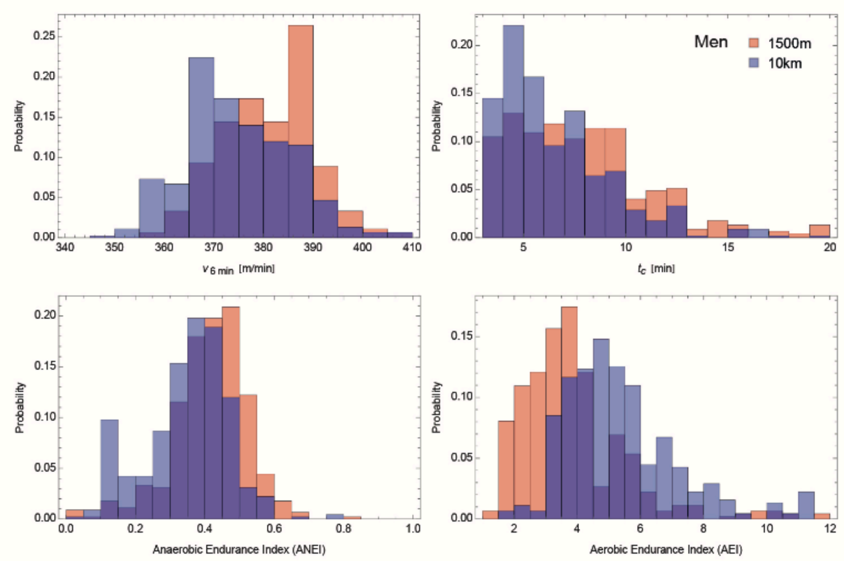
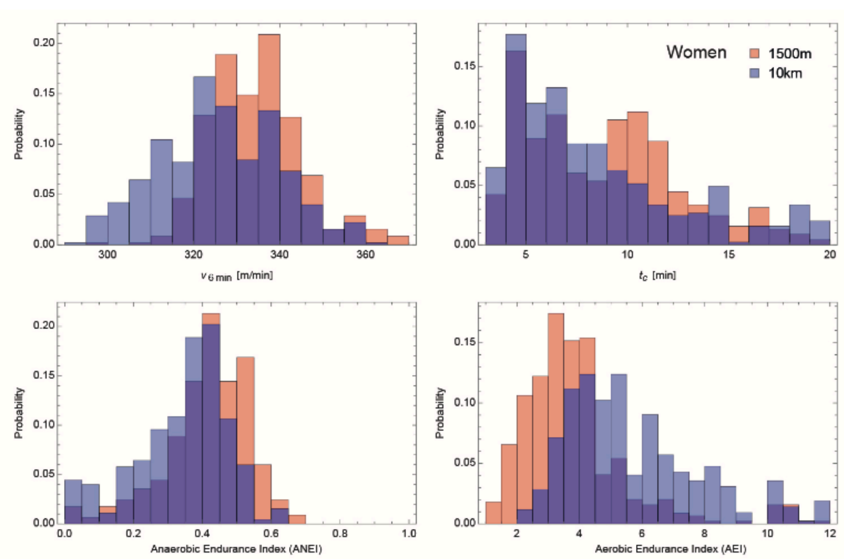


Fig. 2: Histograms showing probabilities for observing physiological characteristics in 1500m and 10km specialists. Top: Men, Bottom: Women. Data: Personal records of runners from the UK (years 2011 to 2015, 450 runners in each of the four groups, source: www.thepowerof10.info)



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Eilish McColgan in action in Berlin.

runners with best consistent performances on the distances of 1500m and 10km. We then applied our model to their PRs and extracted their physiological indices with average values summarised in Tab. 1. Firstly, just using the four indices, our model predicted the runner's PRs with high accuracy with errors of less than 1% (see last line of Tab.1). Secondly, we could find characteristic differences in the indices for British Milers (1500m) and British 10k runners: The typical speed that a runner can maintain for 6 minutes (v_{6min}) is higher for milers than for 10km specialists. Also, the time t_c over which VO2max can be sustained is longer for milers than for 10km runners. The relative contribution of aerobic energy to a race that lasts for a time t_c is slightly higher for the 10k group (about 91% versus 89.4% for milers), probably reflecting more training in the aerobic range. A clear distinction between milers and 10km specialists can be observed from the endurance indices: While the 10km group has a better AEI and hence can sustain for a longer time ($t_{90\%}$) 90% of VO2max, the milers have a better ANEI and can keep up 110% of VO2max for a longer time $t_{110\%}$ than the 10km group. These physiological observations clearly reflect the distinct type of training of milers and 10km runners. Another important observation of our analysis is a large variation of indices among athletes. Fig. 2 shows the probabilities to observe certain values for the physiological indices in the 4 groups of analysed UK runners.

How our model can help runners and coaches for training and racing?

From our model, race performances are predictable for races of any duration from about 100 seconds to 4 hours. Of course this is useful for establishing racing strategies. It is also useful for training when coaches often define paces based on an equivalent distance: 1500m pace, 5k pace, 10k pace or marathon pace for instance. Following the progression of a runner over time, it is also possible to analyse the effect of certain types of training on physiological characteristics.

For instance, a coach might decide to focus either on improving velocity at VO2max or improving aerobic endurance based on the current profile. Also, for recruiting athletes and to decide on their optimal race distance, it might be interesting to understand how the physiological indices compare to the typical distribution of indices in a given group of specialists.

Conclusion

The large amount of data that one can now collect from millions of runners (for example heart rate, power, stride frequency and GPS data) will probably help building better models and understanding human performance and physiology in the future. Our model and its applications demonstrate that performances obtained under real world track or road conditions can now be used to analyse individualised physiological response to training outside the laboratory. Future research on exercise physiology should lead to further improvements in understanding training and performances. The use of connected device, and the large collection of race results, and data from smart devices and sensors could help researchers to understand the complicated relation between training and performances on an individual level. It shall be interesting to apply our model to analyse outside the laboratory the effect of altitude, weather conditions, age of the runner on physiological indices and performance.

Laura Muir competing over 1500m in Rio.

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