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A Systems Model of Training for Athletic Performance

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ABSTRACT. Banister E.W., T.W. Calvert, M.V. Savage and T.M. Bach. *A systems model of training for athletic performance Aust. J. Sports Med. 7(3): 57-61, 1975.*

A model is proposed for describing athletic progress in terms of training and fatigue. Training is considered to be impulsive in character so that each training period exerts an immediate training effect which dies away exponentially during the succeeding interval until the next 'bolus' of training. This effect described by the equation: $dT/dt = k_1 (W-T)$ where the rate of increase in a training effect, which results in an increased performance, is described by the product of a constant k and the difference between the extra stimulation effect of W, which is the training impulse (TRIMP), and the already established training base effect T, also in TRIMP units. The training impulse (TRIMP) is in quite arbitrary units, in this case merely the distance swum each training session expressed in hundreds of metres multiplied by a subjective factor estimate (either 1, 2 or 3) describing the intensity of swimming. The time constant (T_1) for the exponential decay of the training effect is $1/k_1$. The fatiguing effect of training is also described by a differential equation of the same form as the equation for dT/dt with a similar interpretation of the relationship between W and F, $dF/dt = k_2 (W-F)$ where F is a fatigue effect, $1/k_2$ is the time constant of the fatigue effect decay (T_2). This model is interpreted through real training data of a top class swimmer and the concept further discussed.

It is well known that during training for a wide variety of human activities, performance will first improve quickly, later improve more slowly and finally tend to a limit. There is less agreement on the way in which performance falls due to 'overtraining' if a high level of training is maintained indefinitely. Quantitative data relating performance to different programs of training has been obtained by several investigators [1, 2, 8] but it is still difficult to predict the results of a particular training program. A meaningful predictive model of the effects of training might yield a better understanding of the underlying physiological and psychological processes involved and become an invaluable aid both in the choice of optimal training programs for athletes and in the prescription of exercise. Development of a systems model involves: 1) proposing various components of human performance, 2) qualitatively describing their possible interactions and 3) finding quantitative relationships which describe their interactions.

DETERMINANT HUMAN PERFORMANCE FACTORS

Some basic determinants of athletic performance are emotional outlook, level of skill and physical capabilities, including both degrees of fitness and fatigue. There may also be other, less tangible traits not as strongly determinant for the simple model proposed here.

1. Physical capabilities are positively affected by the amount and type of training and negatively by the amount of fatigue that the training itself accumulates in the performer. Changes in physical capability reflect physiological changes; thus in addition to training and fatigue, other factors, such as nutrition, smoking, drinking, drugs, etc. will operate. Fatigue, which results from the daily routine (e.g. exams, amount of sleep, etc) is also a factor to be considered.
2. Emotional factors affect performance in many ways ranging from acute crises to chronic anxiety. The problem of measuring and quantifying these factors is obvious. One may hypothesize that good performances will produce a psychological drive or lift and conversely poor performances will have the opposite effect. It is also a common experience that increasing fatigue will have a negative effect on emotional factors.
3. Skill may be easier to quantify. Increase in skill involves development of a larger, more efficient motor platform, eliminating use of unnecessary muscle groups and developing more precise neurological feedback regarding body position. It is not simply a function of the effectiveness of initial skill training received from a tutor. It involves the amount of individual time spent practicing the particular skill and is thus related to the amount of training done. In addition to this, there may also be another component of skill which one might call racing skill or sense or pace, affected more by the quality or intensity of training than by its actual amount.

The factors hypothesized above and their interactions are summarized in the systems model shown in Fig. 1.

In this paper, an attempt is made to isolate only the training components associated with physical capabilities and quantify their relationship to performance as a first step in developing a more complete systems model together with its full physiological, psychological and neurological skill interpretation.

THEORETICAL CONSIDERATIONS

We may consider training to be impulsive in character so that each training period exerts an immediate training effect which dies away exponentially during the succeeding interval until the next 'bolus' of training. This effect is described by the equation:

$$dT/dt=k_1(W-T) \qquad (1)$$

where the rate of increase in a training effect, which results in an increased performance, is described by the product of a constant k and the difference between the extra stimulation effect of W, the training impulse (TRIMP), and the already established training base effect T. W is expressed in arbitrary units derived from the quantification of training and T is in directly related units. The time constant (T_1) which can be determined from the solution of the differential equation is given by $1/k_1$.

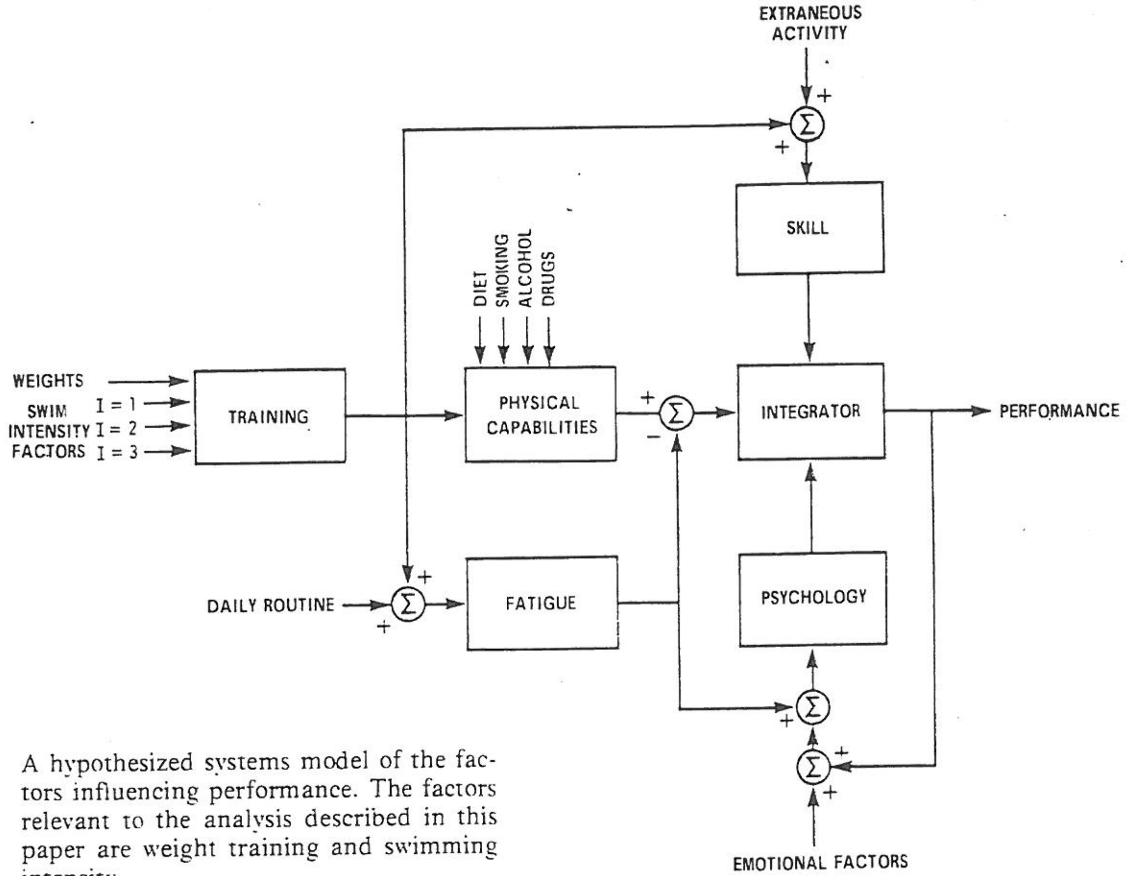

Fig. 1 A hypothesized systems model of the factors influencing performance. The factors relevant to the analysis described in this paper are weight training and swimming intensity.

Paradoxically, the same impulse (TRIMP) which causes a training effect is inherently fatiguing, generating a fatigue effect increase, dF/dt, instantaneously equal to dT/dt. It is easy to conceive that unremitting training is debilitating and performance limiting (7), a concept which fits well within the proposed model. This fatiguing effect of training is also described by a differential equation of the same form as equation (1) with a similar interpretation of the relationship between W and F

$$dF/dt = k_2(W - F) \qquad (2)$$

where F is a fatigue effect. Similarly solution of this differential equation gives the time constant $T_2 = 1/k_2$) for the decay of the fatigue effect. The time constants T_1 and T_2 are different, T_2 logically being smaller than T_1 if a positive increase in performance is to be expected. If T_1 equalled T_2 the fatiguing effect of each training impulse would exactly equal its training effect at all points in time, a phenomenon demonstrably untrue. At any stage of training the difference of the training effect and the fatiguing effect (T - F), should be some measure of a performance level mirroring actual performances throughout the training period.

In the present treatment emotional and skill components were assumed constant but obviously in further studies these must be quantified in some manner. However, the swimmer studied was mature in technique, after several years of swimming, and the criterion performances were time trials somewhat free from the complications of live competition. Thus errors introduced by neglecting emotion and skill components in favour of the physical component of training were assumed to be small.

METHODS

The present model was developed from the training and performance profiles of a top class swimmer (TB) who was studied throughout 105 days of training. Criterion performances quantifying effectiveness of the training regimen consisted of a 100 metre time trial (swimming) once a week and a maximal treadmill run once every two weeks. In the maximal run, heart rates, gas samples and blood samples were collected. A questionnaire was completed every 2 - 3 days recording the swimmer's feelings and attitudes at that time on such simple matters as exhuberence, tiredness and illness. Resting heart rate and oral temperature were taken every 2-3 days. Complete daily work-out schedules were also recorded. Initially using only the criterion swim times and work schedules an attempt is made to model the training effect and fatigue effect with regard to the size of the training impulse. This latter was measured by assessing arbitrarily the quantity and quality of the training as described below. Of course these latter data are those which are most easily collected in an actual coaching situation. The more complicated technical data is not elaborated in this paper and will be reported subsequently.

QUANTIFICATION OF TRAINING

Detailed records of all types of training undertaken were kept. In the water this consisted of easy work, warming up and warming down periods (Intensity= 1); endurance training of harder intensity-long duration (Intensity = 2) and quality training, speed swimming — rest pauses (Intensity = 3). Training distances were designated in hundreds of metres (14,000 metres = 140 units) and the training arbitrarily quantified by multiplying this number by the intensity number of the training (e.g. 140 units of intensity 2 = 280 training units).

Dry land training consisted of weight training different muscle groups by performing a large number of repetitions using small weights. This training was quantified in units of 500 repetitions. A water equivalent of this training was assigned, again quite arbitrarily but according to the 'sense' of the swimmer in his recollection of their equivalent effects. In this way, a unit of weight training (500 repetitions) had the equivalence of 1000 metres of swimming at intensity 3 (i.e. 10 hundreds x 3 = 30 training impulse units). The differential equations 1 and 2 were solved for various values of T_1 and T_2 were found such that performance level values (difference of training effects and fatiguing effects, T - F) expressed in training impulse units, closely approximated the actual criterion time trial profile, expressed in seconds, throughout the training period. None of the physiological or attitude measures were incorporated into quantifying the Training Impulse (TRIMP). This remains to be done subsequently.

BOUNDARY CONDITIONS

Initial levels of training and fatigue at the onset of the period ($t = 0$) were relatively easy to establish. The previous season had been a World Student Games year and the swimmer had been out of the water for only 24 days before commencement of the current season. The time constants of both training and fatigue decay may be assumed sufficiently small that little if any of the initial training and fatigue effects remain at the end of 105 days of training, especially in the case of a top class performer when only small performance gains are being made each season. Thus, if final values of fatigue and training are assumed independent of the initial conditions, we have a method to estimate these same initial conditions. The fundamental assumption is that the swimmer at the end of the 105 day period under study was performing at the same level as at the end of his previous season (for which, unfortunately, no quantitative data is available). As a next best estimate of these initial fatigue and training conditions their values at the end of the current season (i.e. the 105 day period) were taken and allowed to decay for 24 days according to the time constants T_1 and T_2. Successive iteration and approximation of predicted performance levels to actual levels was performed to minimize the error of estimation and resulted in the best correlation of both performance estimation (from training) and criterion performance (from time trials). Optimal values for T_1 and T_2 were thus obtained. The optimization was performed with the aid of an interactive computer graphics terminal (Tektronix 4103) connected to an APL language system (IBM 370/155 at SFU). Initial values were guessed and successively modified until optimal correspondence between the actual swim time trials and the profile of the predicted performance levels was obtained.

RESULTS

Table 1 shows representative values throughout the training period quantifying the training impulse (TRIMP) with respect to the intensity of swimming and weight training. In this table computer estimation according to the solution of differential equations 1 and 2 gives optimal values for the training (T) and fatigue (F) effects a value (T - F) which represents a performance level, in units of the TRIMP, relevant to a particular time in the training period. The time constants T_1, T_2 and best estimates of the initial training and fatigue levels are also indicated.

Fig. 2 shows training and fatiguing effect curves and the training impulse (inset) throughout training. It is easily apparent that the onset of heavy training has a debilitating effect on performance level or potential since the fatigue level quickly assumes significant proportions and by the 15th day of training is greater than the training effect. As the trainee 'peaks' towards competition swimming, 21 days before the end of the training period, by eliminating endurance swimming and long work-outs from his training routines, the training effect becomes predominant once more and both performance levels (T - F) and criterion time trial performances improve.

Fig. 3 shows the performance level graph (T - F) throughout the training period. This graph is continued to day 135 with the condition that all training was eliminated from day 105 onwards. A pronounced recuperative rebound effect is apparent before the effect of 'no training' emerges once more as a slight decline in performance level.

TABLE 1

Showing the quantification of training at specified times throughout 105 days of the training period and a prediction of performance level for 130 days when no significant formal training took place in the intervening 25 days. Time constants of training (T_1) and fatigue (T_2) from interactive modelling were 50 and 15 days respectively.

Day	Swim Distance (metres x 10^{-2}) and Intensity [a] 1	2	3	Weight Training Reps. [b]	Training Impulse TRIMP [c]	Training Effect (T)	Fatigue Effect (F)	Performance Level (T - F)
0					0	50.2 [d]	13.9 [d]	36.3
0	14	53	0·5	300	139.5	51.9	21.7	30.2
8	10	40	0	467	118.0	56.8	45.1	11.7
24	1	115	0	497	260.8	65.8	72.8	-7.0
50	10	89	4	561	233.7	91.7	126.8	-35.1
75	12	4	0	0	20.0	93.4	94.8	-1.4
100	21	6	5	0	48.0	82.3	69.2	·13.1
105	14	20	0	0	54.0	81.1	81.1	·12.3
130	0	0	0	0	0	49.4	13.7	·35.7

[a] Arbitrary Training Units = metres x intensity number (1, 2, or 3)
[b] 500 reps = 1000 metres swimming at intensity 3 i.e. 30 Training Units
[c] TRIMP = Σ swim training units + weight training equivalence
[d] Estimated from model $T_1 = 50$, $T_2 = 15$ and T and F allowed to decay for 24 days from day 105 with no formal training input.

Table 2 shows actual criterion swim times together with those estimated (modelled) from the performance level (T - F) at the particular time when the criterion time trial took place. In this estimation, a direct proportionality was assumed between one estimated performance level (T - F) in arbitrary TRIMP units and the time in seconds of the relevant swim trial. By choosing any one point to establish a proportionality constant a prediction of all other swim trial times could be made according to the (T - F) score at the time of the swim trial. The error of these estimations was minimized statistically and the values in the modelled column of Table 2 are the end result of this procedure.

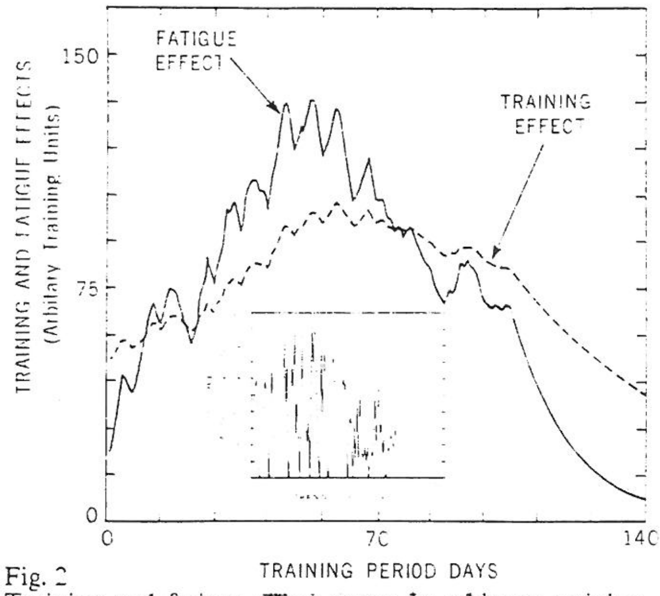

Fig. 2
Training and fatigue effect curves in arbitrary training units throughout 105 days of training. The inset shows the training impulse (TRIMP) on each day of training in compatible units.

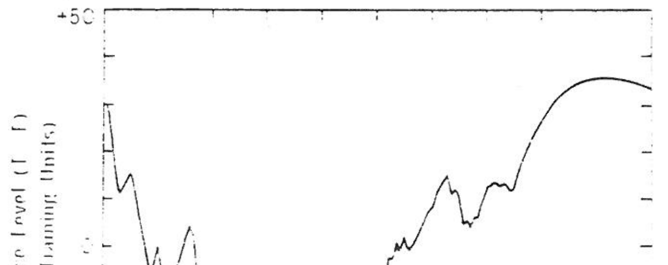

Fig. 3
Performance level or potential for performance in terms of the difference between the training and fatigue effect throughout the training period. The smooth portion of the curve from day 105 onwards predicts that the potential performance after formal training sessions ceased would increase to an optimal level even greater than the point to which the athlete was actually tapered by decreasing the intensity of training. Ultimately decline in performance occurs as a decrease in the training impulse begins to make itself felt also on training (T) level as well as on fatigue (F) levels.

TABLE 2

Showing actual and predicted criterion swim times at specified times throughout training. The predictions were made from the model using time constants of 50 and 15 days respectively for the training and fatiguing effect of the TRIMP.

DAY	ACTUAL SWIM TIME (Seconds)	MODELLED SWIM TIME (Seconds)
8	56.5	56.5
15	56.8	57.1
29	56.5	57.4
37	57.8	57.6
43	58.1	57.8
52	57.9	58.1
59	58.4	58.0
78	57.3	56.9
92	56.9	56.7

DISCUSSION

The analysis of this paper refers to the preparation for competition undertaken in 1973. The decrement in time trial criteria at different points in the athlete's preparation for 1973 competition (Fig. 3) stands in marked contrast to a previous steady increment in his yearly best performance marks from 1967 to 1973. These contrasting performances i.e. those within a year during the process of preparing for competition compared to those across the years, when optimal preparation for competition has been completed, highlight the comments of Prokop on the consequence of overtraining. It is clear that training itself is debilitating when it is of sufficient intensity to change physiological systems and that good performances are achieved only when recuperation is allowed prior to performance. If no recuperative periods are allowed, either by complete rest or by an alleviation of the intensity of training, then performance will decline despite continuation of the training.

Improved world record performances described by Frucht and Jokl [3] reflect the interaction of both training and its debilitating effects (fatigue). World record performances represent an optimization of the two effects where withdrawal or modification of training allows maximum benefit to be achieved by decreasing the fatigue effect before the training effect itself also begins to decline by receiving no continuing stimulus. Thus, world record performances have grown in a logarithmic fashion and tend to a limit which may be predicted. The problem facing us is to predict the necessary performance for future success (i.e. world or Olympic records of the future) and to control the training process so that these predicted levels are achieved by an individual within a prescribed period (i.e. from his present level to when the predicted level is required). This paper presents data which allows the training process of an individual to be followed and his reaction to debilitating (fatiguing) training and subsequent 'taper' to be quantified, however simply, given our present state of sophistication in incorporating all the contributing components of the training process.

Improved athletic performance in recent years in events where equipment and technique have remained relatively constant cannot be rationalized solely by improved human nutrition, stature or other physical traits. Aerobic capacities of past champions were comparable with modern athletes (VO_2 max of 60→80 ml kg^{-1}min^{-1}) [4]. Similarly, genetic limits of functional ability have been described by Klissouras [5,6] where a strong adaptation. It is hard to imagine that training, within a relatively short time span of 70 years (1900 — 1970) when performances have improved dramatically, can have

Professor John Bloomfield is currently the Head of the Department of Physical Education and Recreation at the University of Western Australia. His wife, Noelene, is a foreign language teacher at the same university and they have three children.

Professor Bloomfield completed his Diploma of Physical Education at Sydney Teachers College (1953) and after teaching physical education in New South Wales on a Fullbright Scholarship in 1960. At the University of Oregon he completed a Master of Science degree with Honours (1964) and then proceeded to Ph.D. (1967).

While in Oregon he was the head coach of the Eugene Aquatic Club (1960-64) instructor in functional anatomy (Department of Biology) and exercise physiology (Department of Physical Education) (1964-67).

Australia was fortunate that John Bloomfield saw fit to return home late in 1967 where he in turn, became Senior Lecturer, Associate Professor, Head of Department and subsequently Professor of Physical Education and Recreation at the University of Western Australia.

He has participated in a wide range of sports, most notably as an Australian surf swimming representative 1953-56, and during the past 10 years has undertaken lecture tours of South East Asia the Middle East, Eastern and Western Europe, North America and the Pacific region.

Professor Bloomfield has also been Deputy Chairman of the Western Australian State Government Community Recreation Council (1973-75), National councillor for the Australian Council for Health, Physical Education and Recreation (1973-75), National councillor for the Australian Sports Council (1974-75) and President of the Australian Sports Medicine Federation during 1972-73.

In addition to 35 academic and professional papers, Professor Bloomfield has written a book entitled 'Know How in The Surf' (3 editions 1959-65) and an Australian Government Report 'The Role, Scope and Development of Recreation in Australia,' (1974).

John Bloomfield has, by any standards, certainly packed many experiences into his 42 years and has played a magnificent role in the development of physical education and recreation in Australia as well as contributing largely to sports medicine. Currently he is on study leave from the University of Western Australia taking what everybody must agree to be a well earned change of pace.

DISCUSSION (CONT).

'engineered' a new genetic limit. On the basis of the present model, the improvement may be explained in terms of: 1) changes in the intensity of the training process (where no irreversible debilitation is induced) and 2) greater appreciation of the intricacy of the training processes. It is quite obvious that the second observation has been qualitatively appreciated by generations of coaches because of the integral place 'tapering' has held in their programs. To many, this may have been viewed as an art; it now seems that indeed it may be more precisely quantified.

It must be emphasized that the present data is relevant for one particular individual. The model, particularly as it is expanded to incorporate physiological and psychological inputs, has to be generated for each new individual so that specifically relevant training curves are produced for him. No longer can 'blanket' methods of training be applied if individual optimal results are to be achieved. The present method models the training process using only data from the amount of training done and a criterion all-out performance in the activity which is regularly performed throughout the training regardless of how good or ill-prepared the athlete feels. In this way individual variability may be appreciated and preparation for competition more relevant to an athlete's inherent capacity may realize more of his true potential.

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