Estimation of Physical Performance Level of Man in Long Space Flight Based on Regular Training Data

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Abstract. In this paper, we consider the problem of estimation of physical performance level of cosmonauts in long-term space flight, given the data collected during regular locomotor training exercises. The physical performance level of a cosmonaut is measured in terms of "physiological cost" of work, which is calculated as a function of heart rate, running speed and axial load. An algorithm for estimation of the physical performance level, using the data on the regular training on a treadmill is proposed. The algorithm is based on the principles of linear extrapolation and bisection search. The proposed algorithm is tested on the real data measured in the regular training of Russian cosmonauts on board of the International Space Station and compared to a more simple approach and the standard onboard test of physical performance level. The experimental results suggest that the proposed algorithm may be useful for the estimation of the physical performance level of cosmonauts in long-term space flights.

Keywords: Physical performance, long space flight, locomotor training, extrapolation, bisection

1 Introduction

The main physiological systems that determine human performance at weightlessness are the cardiovascular, respiratory, and motor systems. All of these systems have significant structural and functional rearrangements during space flights [8–10]. Adaptive rearrangements of these systems in microgravity lead to a decrease of physical performance and requires adequate countermeasures in long term space flights. Physical exercise is the main method of maintaining the level of physical performance, functions of the nervous, neuromuscular, bone systems, motor control systems, and orthostatic tolerance in weightlessness [10].

Currently, prevention of decrease of physical performance level of cosmonauts is mainly attained by the locomotor training on treadmill with an appropriate axial load, supervised by experts on the ground [2]. Walk and run on a treadmill demand maintaining the posture, provide adequate sensory stimulation for the tonic muscles, and ground reaction forces comparable with locomotion on the Earth [2]. Axial loading during locomotion is created by a special training-load suit. The total load from the shoulder belts and the belt located on the hips of the cosmonaut determines the amount of load created by the cosmonaut on the treadmill. The axial load is measured as the total applied kilogram-force, expressed as a percentage of body mass.

The first on-board automated system of training process control was developed, based on an expert system [12]. Unfortunately, this system demonstrated unsatisfactory results in Mars-500 on-ground modelling experiments [3]. We expect that a successful development of an on-board automated system requires problem-tailored data analysis methods to process the measurements form daily training, and one of the key parameters is the performance level.

Currently, the performance level of a cosmonaut and the efficacy of countermeasures are estimated by means of a standard treadmill test designated "MO3", which is performed approximately once a month. The performance level of a cosmonaut is measured in terms of the so-called "physiological cost" of work, which is calculated as a function of heart rate, running speed and axial load [2]. Regression analysis of the physiological cost index on the basis of MO3 tests and optimization of training parameters was done in [1].

It is well known that the heart rate is subject to fluctuations, caused not only by the training load and physical state, but also mood and time of the day [4]. Besides that, the measurements of heart rate during the exercise are subject to noise [5] especially onboard the International Space Station (ISS), where radio interference from other equipment may cause additional errors.

The MO3 test puts a significant strain on a cosmonaut, which makes it impossible to perform it frequently. Therefore it is important to develop a method for estimation of physiological cost using the measurements collected during the regular training without the MO3 procedure.

The aim of the current paper is to enable estimation of the performance level of a cosmonaut for effective management of the physical training on board, using *daily* training data on the running speed, treadmill settings, and the heart rate.

Our study involves identification of time intervals for reliable parameters estimation, censoring the input data and extrapolation of the observed measurements to the corresponding values in conditions of the MO3 test. The analysis based on daily physical training data of Russian cosmonauts on board of the ISS indicates that the estimates of the physiological cost obtained from the regular training tend to agree with those computed in the standard onboard MO3 tests. Finally, some similarities and differences in physical performance evaluation and modelling in sports and in conditions of a space flight are discussed.

2 Regular Training and the Standard Performance Test

The Russian program consists of exercises performed twice a day for a total of 150 min daily. Every day the crew members were recommended to use a treadmill (BD 2) and a cycle ergometer, alternating with the Advanced Resistive Exercise Device (ARED). BD 2 allows two modes of operation: active, i.e., motor-driven, and *passive,* i.e., leg-driven. The passive mode requires more effort than the active mode at any particular speed and axial load level.

Locomotor exercises consist of running and walking on a treadmill, scheduled in a 3-day microcycle. Every day, a training period starts with a passive locomotion and includes two intervals of walking and running [2]. The days of the standard microcycle are illustrated in Fig. 1. Approximately 30 days prior to landing, crew members were advised to perform locomotor exercise two times a day, with the second microcycle identical to the one done on Day 1 in order to increase orthostatic tolerance and vascular tonicity. Also, the microcycle schedule may be modified on some days due to other activities onboard ISS.

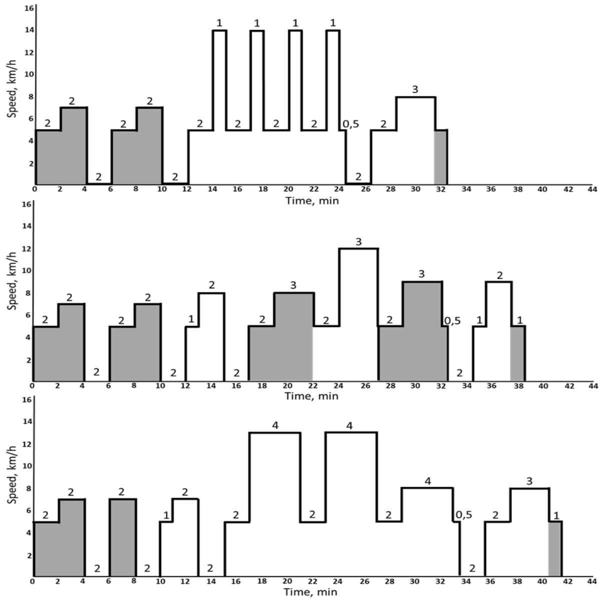

Fig. 1. Three days of the standard microcycle: grey color indicates the passive mode of the treadmill, white color indicates the active mode of the treadmill

The following parameters of locomotor training were evaluated during the exercises on treadmill BD 2: speed in the range of 4 to 20 km/h, weight loading (axial load), the heart rate (using Polar H2), and the treadmill belt mode.

In the long-term missions on ISS, the cosmonaut's performance was monitored on a regular basis. Performance of locomotor exercise was monitored using weekly downloads of the treadmill data. Besides that, several times during the flight the physical endurance of the crew and the efficacy of countermeasures were assessed by means of the standard MO3 test. The MO3 test was carried out when the treadmill functioned in the passive mode and included the following five steps: 3 min of warm-up walk, 2 min of slow running, 2 min of running at a moderate speed, 1 min of running at a maximum speed, and 3 min of cooling-down walk. The sequence and duration of the steps are preprogrammed, but the speed at each stage can be chosen individually. Heart rate (HR), speed, and the axial load levels are the key parameters used for analysis of MO3 results.

In the present paper, the performance capacity at MO3 test is assessed with respect to the physiological cost PhC of work (physiological cost index) calculated as a ratio of heart rate at the end of a running stage HR (bpm) to the running speed of the stage V (km/h) and axial load L (percent of bodyweight):

$$PhC = \frac{HR}{V \cdot L}. \tag{1}$$

The value PhC is evaluated for the stages of slow running, medium running and fast running. We denote these measurements respectively by PhC_s, PhC_m, and PhC_f. In practice, the most informative indices are PhC_m and PhC_f. Based on the data from the MO3 test, the physical endurance is assessed, and corrections are formulated and uplinked by the flight surgeon, if needed.

3 Methodological Constraints

During a training on Earth, a coach besides the heart rate measurements, is able to evaluate the physical condition of a sportsman and the hardness of an exercise on the basis of visual contact and audio communication with a sportsmen. In the case of workout on treadmill onboard, such sources of information are not accessible to the flight surgeon.

The performance level of a cosmonaut may be calculated as described by the expression (1), where the nominator is the heart rate value. Such choice for the nominator in the physiological cost formula may be seen e.g. in [6]. More often in the recent publications the physiological cost is computed as

$$PhC = \frac{\Delta HR}{V \cdot L}, \tag{2}$$

where ΔHR is the *heart rate reserve*, i.e. heart rate after load minus heart rate at rest, see e.g. [2]. The heart rate reserve is less sensitive to the individual differences but requires a measurement of the heart rate at rest. In general, the performance indices based on heart rate increase are shown to be a valuable index of performance ability in [11]. However, if the physiological cost of work is predicted on the basis of the daily training, then the heart rate reserve is difficult to estimate since there is no measurement of the heart rate at rest before regular workouts in the current schedule of locomotor training. For this reason, in what follows, we use the physiological cost of work, given by expression (1).

It should be taken into account that during the regular training, a cosmonaut may choose the axial load different from the recommended value due to his/her personal preferences or the current physical state and this setting can be changed in the course of one training session. Besides that, in some stages of the training, the cosmonauts can choose the running speed different from the recommended value. This variability of the axial load and the running speed create a significant difficulty in estimation of physical performance on the basis of regular training.

The heart rate measurements during the MO3 test and during the regular training are subject to fluctuations, caused not only by the training load and physical state, but also mood and time of the day. Besides that, the measurements of heart rate during the exercise are subject to noise. Our preliminary analysis of onboard training data showed that in some cases HR records contain inadequate entries, which may be caused by the radio interference, a lack of contact of Polar with the body or hardware failures. Inadequate high values of HR may also be caused by some physical activity in a time period preceding the considered training period.

4 Estimation of Physiological Cost from Regular Training

In this section, we describe the algorithm for estimation of physiological cost, which, given the data recorded during a one-day regular training period (and maybe several preceding days), computes an estimate of the value PhC for medium speed running stage, as if the MO3 test were performed on this day instead of the regular running exercise. By the definition of PhC, we need the values of axial load, running speed and the heart rate. As it can be seen from Fig. 1, each of the standard three days contains a 10 min. interval in passive mode in the beginning of workout. Such an interval of each training session was the subject of the analysis described in Subsections 4.4, 4.1. In Subsection 4.3, we develop a personalized version of the formula for PhC, applicable for a wider range of speed values in comparison to formula (1).

4.1 Search for a Time Interval to Estimate the Physiological Cost

As the MO3 test is performed in passive mode of the treadmill, it is necessary to identify an appropriate time interval I in the first 15 min of a training session.

Finding a Maximum Duration Interval with Speed in Given Range. Given the lower and upper bounds V_{min} and V_{max} for admissible speed values, we can look for the time interval $I_{\max}$, such that only few observations with a speed value outside the range $[V_{min}, V_{max}]$ are allowed, but the total number of such records in the interval should not exceed a threshold of 5%. Another requirement imposed on the time interval $I_{\max}$ is that the entries of HR value outside the allowable range of $[HR_{min}, HR_{max}]$ (boundary values $HR_{min} = 60, HR_{max} =$

220) are allowed, but only up to 10% of the total number of records in $I_{\max}$. The thresholds of 5% and 10% are introduced in order to accommodate some noise, which is present in the measurements of speed and heart rate.

The described algorithm for finding an interval $I_{\max}$ has a drawback that it requires a sufficiently narrow interval $[V_{min}, V_{max}]$, which is hard to define a priori. If the interval $[V_{min}, V_{max}]$ is too narrow, then the identified $I_{\max}$ may be shorter than required for estimation of HR, caused by the running during this interval (e.g. less than 1 min). If the interval $[V_{min}, V_{max}]$ is too wide, then the physical load may change significantly during this interval, which is inconsistent with the MO3 principles and the average speed in this interval does not characterize the training dose properly. As a simple choice for interval I, we can choose $V_{min} = 5$ km/h, $V_{max} = 8$ km/h, attempting to cover the typical range of speed in passive mode onboard training and put $I := I_{\max}$. In the next paragraph, we describe a method for finding V_{min}, V_{max} automatically.

Finding a Time Interval with Small Variation of Speed. For each given workout, we can look for an interval in the passive mode of at least 1.5 minutes in length with the least variation of speed during the interval. Minimization of speed variation is aimed at finding an interval I with uniform physical load, which would be similar to a 2-min stage of medium run in the MO3 test.

Suppose that a lower bound V_{min} of acceptable speed for interval I is given. We search for the minimal upper bound V_{max}, using the following Bisection Algorithm. This algorithm iteratively reduces V_{max}, while a longest interval with speed in $[V_{min}, V_{max}]$ is at least 1.5 min long. The maximum duration interval $I_{\max}$, where the 95% of speed values are in the range $[V_{min}, V_{max}]$, is found by the procedure described in the previous paragraph. The given value V_{min} remains constant in Bisection Algorithm. The value V_{max} on the input of Bisection Algorithm is set to $V_{min} + 4$ km/h. The iterations of Bisection continue until two consecutive values of V_{max} will differ by at most 0.1 km/h or until a failure to find an interval with speed in range $[V_{min}, V_{max}]$ will occur. The last I_{max} computed in this algorithm is considered as an output of Bisection Algorithm.

The Bisection Algorithm is called iteratively with $V_{min} = V_{slow}^{med}, V_{slow}^{med} + 0.5, \ldots, V_{med}^{fast}$, where V_{slow}^{med} is the threshold between the slow and medium speed, and V_{med}^{fast} is a threshold between the medium and the fast speed, defined by the available MO3 tests for this cosmonaut (onboard or on Earth). Let V_s, V_m and V_f denote the speed in slow running, medium running and fast running stages of the available MO3 test. Then we define $V_{slow}^{med} := \lfloor V_s + V_m \rfloor / 2$ and $V_{med}^{fast} := \lfloor V_f + V_m \rfloor / 2$. An interval with the least variation of speed, found in the loop over all $V_{min} = V_{slow}^{med}, V_{slow}^{med} + 0.5, \ldots, V_{med}^{fast}$, is returned as the interval I.

Censoring Time Intervals. To exclude inadequate entries in the HR records, we checked that the value HR in the end of interval $I_{\max}$ exceeds the HR value at the beginning of $I_{\max}$ at least by 10 bpm (this is expected as a result of workout).

To avoid undesired high values of HR, caused by high load in preceding time, we checked (i) that the value of HR at the beginning of a training session does not exceed the average initial HR over all training sessions by more than 10 bpm, and (ii) that during a 1-minute interval preceding the interval $I_{\max}$, the average treadmill speed does not exceed the average speed of $I_{\max}$ by more than 1 km/h.

4.2 Extrapolation of Heart Rate to the End of 2-Minute Interval

According to the outline of MO3 test, the heart rate is measured in the end of each 2-min interval of constant load. A preliminary analysis of HR data recorded during MO3 tests indicates that the HR grows nearly linear during each 2-min stage. The duration of the chosen interval I of regular training is usually different from 2 min, therefore, it may be necessary to extrapolate the heart rate to a *supposed* 2-minute duration of the interval. Let us assume that the end points of the interval I are t_1 and t_2, i.e. $I = [t_1, t_2]$ and denote $\Delta t := t_2 - t_1$.

If $\Delta t < 2$ min, then HR is extrapolated as follows. Calculate the average heart rate for the first and last 10% of the interval I. These values HR_0 and HR_1 are considered as the heart rate estimates for the moments $t_1 + 0.05\Delta t$ and $t_2 - 0.05\Delta t$. Next, compute the coefficients A, B of a linear function $HR(t) = tA + B$, such that $HR(0.05\Delta t) = HR_0$ and $HR(0.95\Delta t) = HR_1$. Then the heart rate extrapolation to the end of min 2 is computed as $HR(2)$.

In case $\Delta t \geq 2$ min, it is sufficient to compute the average HR starting from the moment t=1.9 min till t=2 min on the interval I.

4.3 Estimation of Physiological Cost at Different Running Speed

Formula (1) was intended to measure PhC_s, PhC_m, and PhC_f, when the cosmonaut is running a particular MO3 stage, and these values can differ significantly in one MO3 test. It is necessary to modify expression (1) for estimation of PhC_m in running with a speed, which may significantly differ from the speed V_m in medium stage of MO3 test. To this end, we substitute V in (1) by a linear expression $a + bV$, where the coefficients a and b are found from the equations

$$\frac{HR_s}{(a + bV_s)L} = \frac{HR_m}{(a + bV_m)L} = PhC_m. \tag{3}$$

Here HR_s, HR_m, and HR_f are the heart rates in slow, medium and fast stages. The three equations given in (3) mean that due to the linear expression $a + bV$ in the denominator, the same value of PhC_m should be found from the data collected in the medium running stage as well as in the slow running stage of the MO3 test, using the new expression

$$PhC = \frac{HR}{(a + bV)L}. \tag{4}$$

4.4 Estimation of Axial Load Recorded During Regular Exercises

In order to censor out the invalid measurements of the axial load, two parameters L_{min} and L_{max} were defined on the basis of the known rules for choosing admissible axial loads during onboard training: $L_{min} = 35, L_{max} = 75$. A preliminary analysis of the registered data showed that, during the exercise, the axial load is sometimes measured with random negative error. In order to reduce such errors in our analysis we consider the maximum value of the observed axial loads in the interval $[L_{min}, L_{max}]$ during the training session. If the training session does not contain any values from the $[L_{min}, L_{max}]$ interval, then the value L is set equal to the axial load in the nearest preceding day when this value was valid, if such a day is found within 10 calendar days (otherwise a workout is discarded).

4.5 Physiological Cost Estimates and the MO3 Results

In order to evaluate the methods proposed in Section 4, we carried out a statistical analysis of available data for 14 cosmonauts who participated in long-term space flights. The first MO3 test in each flight was used for computing coefficients a and b by equations (3). In the statistical analysis, we computed the correlation coefficient ρ between PhC_m from the second MO3 test in each flight and the PhC estimates based on training sessions. In view of high variability of single-day estimates from training data and frequently missing data (approximately in 10%-30% of the days the valid data were absent), we considered the estimates in each period starting five days before the second MO3 day and ending five days after this day. The PhC estimates from training data in this period were averaged and compared to the PhC_m from the corresponding MO3 test.

Formula (1) applied to the maximum duration interval I_{max} yielded an estimate with $\rho = 0.772$, while the modified formula (4) applied to the interval I found by the Bisection Algorithm yielded an estimate with $\rho = 0.943$. We also performed the Student test for statistical difference in means of the PhC_m at the second MO3 test and the PhC estimates averaged over the closest 5 days as described above. For both of the considered estimates based on the training data, the Student test did not indicate any statistically significant differences, even with significance level $p = 0.1$, i.e. a systematical error is not found.

The physiological cost estimates as well as the values of PhC_m from the onboard MO3 tests for two individuals are illustrated in Fig 2. It can be seen from the figure that application of the new formula (4) to the measurements from the interval I, found by the Bisection Algorithm, tend to give more accurate estimates of PhC_m than the straightforward application of formula (1) to the measurements in maximum duration interval $I_{\max}$. The coefficients a and b are identified according to (3) on the basis of the first MO3 test in the flight.

5 Discussion

Training on the treadmill onboard ISS has many common features with the training of sportsmen on Earth: In both cases the training dose is carefully measured and recorded, the training schedule is split into micro-cycles, a specific date for achieving maximal performance is given in advance (a competition date for sportsmen and a landing date for cosmonauts), noisy measurements of heart

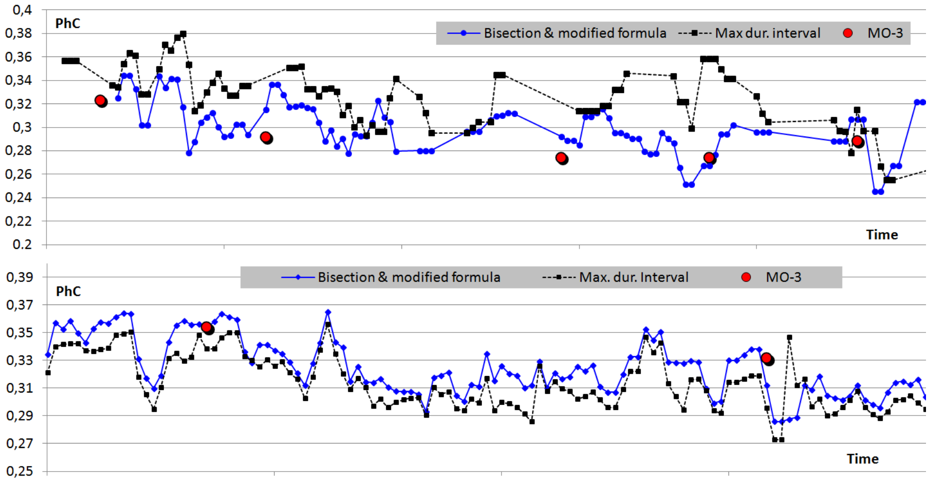

Fig. 2. Results of MO3 test and two estimates of physiological cost: (i) formula (1) applied to the maximum duration interval I_{max} and (ii) the modified formula for physiological cost applied to the interval I found by the Bisection Algorithm. Each node shows an average of estimates for PhC computed in three subsequent days of a flight. The duration of time intervals between the marks on the horizontal axis is 30 days.

rate during exercises should be taken into account [5], etc. But also some important differences take place. In particular, the amount of training on the treadmill onboard ISS is chosen in such a way that no overtraining should occur. Therefore it is expected that the anaerobic threshold in training onboard the ISS will not be passed [7], and identification of this threshold is unlikely to be a useful measure of cosmonauts physical performance. Also, it is problematic to measure the blood lactate level onboard, because the procedure of blood collection and its analysis is complicated on the ISS. Therefore the heart rate dynamics during the exercises appears to be the most appropriate source of information about the cosmonauts physical performance level.

6 Conclusions

An algorithm for estimation of the physical performance level of a cosmonaut, using the data on the running speed, axial load and the heart rate in regular training on a treadmill is proposed. The algorithm is based on a modified expression for the physiological cost index and an adaptive search for a time interval, which is similar to one of the stages of the standard MO3 test for physical performance level. Preliminary results of the proposed algorithm suggest that it may be useful for the estimation of the physical performance level of cosmonauts in long-term space flights.

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