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Estimation of the Maximal Work Rate Sustainable for 6 Minutes Using a Single-level Load or Stepwise Increasing Loads

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ABSTRACT

Twenty-seven young men participated in four different types of maximal work tests: the Tornvall maximal ergometer test with a constant load and a work time of about 6 min, a maximal work test with two increases in load after 12 and 18 min work and a work time of about 21 min, a work test with increase in load every 6th minute until exhaustion, and a maximal work test on constant load during which maximal oxygen uptake was determined. A method based on the relationship between log load and log work time is proposed for estimation of physical work capacity expressed as $W_{max\ 6\ min}$ from work tests with increasing loads. $W_{max\ 6\ min}$ calculated in this manner differs very little from the results obtained from a work test with a constant load and a work time of about 6 min (the Tornvall test) and the coefficient of correlation and standard error of residuals are of the same magnitude ($r = 0.95$—0.97; $s_e = 64 - 88$ kpm $\times$ min^{-1}) as those obtained from a test-retest of the Tornvall test (r = 0.97; $s_e = 59$ kpm $\times$ min^{-1}). The Tornvall test also shows a very strong relationship with the maximal oxygen uptake (r = 0.88).

On the basis of earlier studies (1, 4) and his own investigations Tornvall (8) assumed that a linear relationship existed between the logarithms for maximal work time and load for work on a bicycle ergometer. This relationship may be expressed as follows:

$$\log T = \alpha + \beta \log N + e \qquad (1)$$

where N = load, T = maximal work time at load N, α and β = constants, and e = a remainder term caused by disturbing factors.

Tornvall tested a number of individuals (including 52 conscripts and 28 other young men) at different loads and calculated the mean of the individual estimates of β. This was -4.959 for the conscript group and, with the aid of this value, Tornvall stated that one could estimate the highest load an individual can sustain for 6 min ($W_{max\ 6\ min}$) by letting him work to exhaustion at an arbitrarily selected load and inserting the values for T and N in the equation

$$\log W_{max\ 6\ min} = \frac{\log T - \log 6}{4.959} + \log N \qquad (2)$$

In the case of work times of less than 1 min or more than 18 min a new test must be made at a more appropriate load, as it had not been confirmed whether the equation held good also for work of shorter or longer duration. Tornvall also stated that the estimate became considerably more reliable if the range for permissible work times was reduced to 1–12 min.

As a new system for registration of conscripts into the Swedish armed forces was being investigated, it was suggested that the medical examination should include a work test *ad modum* Tornvall. The primary idea was that, to simplify the examination procedure in the new system, all draftees should be tested at the same load (1 400 kpm $\times$ min^{-1})[1]. A pilot study, however, showed that about 25% could sustain this load for more than 12 min and about 9% more than 18 min. In a discussion of the results of the pilot study the present author suggested that, by raising the load by 200 kpm $\times$ min^{-1} after 12 min, the proportion of those exceeding the 18-min limit would be reduced and that, for those exceeding this limit, the test should not be interrupted but that the load should instead be raised by an additional 200 kpm $\times$ min^{-1} every 6th minute.

The first aim of the present study was to test the Tornvall procedure and to compare the results obtained at a constant load and work time between 2 and 12 min with

1) a maximal work test in which the load is raised

[1] 1 kpm $\times$ min^{-1} = 0.1634 watt; 1 watt = 6.118 kpm $\times$ min^{-1}.

Table I. *Physical characteristics and selected data on physical working capacity for the 27 subjects and 18-year-olds at registration (n = 1718)*

Variable	The subjects $\bar{x}$	S.D.	Range	Boys of 18 $\bar{x}$
Age, years	22.37	22	18.7–27.0	
Height, cm	180.6	6.9	169–192	177.2
Weight, kg	67.8	7.8	54.5–85.0	66.4
Heart volume, ml	734	98	520–910	673[a]
$W_{max\ 6\ min}$, kpm × min^{-1}	1 616	241	1 180–2 002	1 451
Maximal oxygen uptake l × min^{-1}	3.406	483	2.65–4.39	
ml × kg^{-1} × min^{-1}	50.4	6.4	37.5–63.4	

[a] Calculated from micro X-rays taken in a standing position.

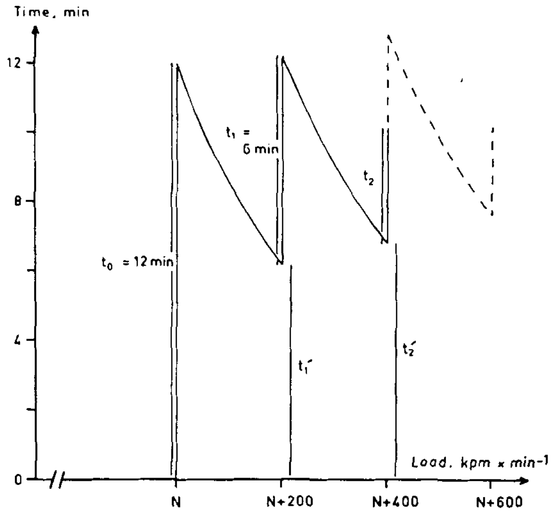

Fig. 2. Recalculation and addition of work times in work test type *b*. See text.

after 12 min by 200 kpm × min^{-1} and after 18 min by an additional 200 kpm × min^{-1} and the total work time is at least 18 min,

2) a graded maximal work test in which the load is raised by 300 kpm × min^{-1} every 6th minute until exhaustion.

Another aim was to study the reliability of the original Tornvall test, at a constant load and with a work time between 2 and 12 min, and the relation of this test to maximal oxygen uptake.

MATERIAL

The material consisted of 27 male university students. The subjects applied in response to an advertisement and received a remuneration which covered their travel expenses and offered a moderate stimulus.

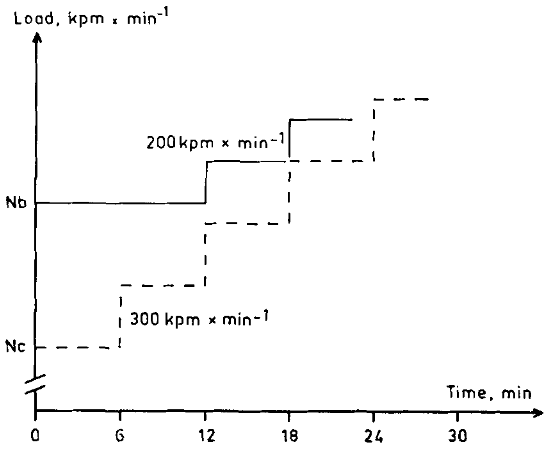

Fig. 1. Sequence of change in load. *Nb* = initial load work test type *b*. *Nc* = initial load work test type *c*.

Data of the 27 subjects will be seen in Table I, from which it appears that the subjects were somewhat older and very slightly taller and heavier than 18-year-old draftees and that their working capacity measured as $W_{max\ 6\ min}$ was considerably higher.

METHODS

Height was measured to within 1 cm and weight to the nearest 0.1 kg. Heart volume was calculated according to the formula proposed by Kjellberg et al. (3) from anterio–posterior and lateral roentgenograms, taken with the tube at right angles to the table. The subject was placed in a supine position with cranially extended arms.

ECG was recorded at rest with 11 leads on an Elema–Schönander Mingograf 42 or 34. $CH_2 - CH_7$ were recorded during the first work test, CH_4 in the others.

The tests were carried out on an electrically braked ergometer—Elema-Schönander Model AM 368 (2). No changes were detected in the calibration when the ergometers were checked before, during and after the experiment. The length of the pedal lever was 17.5 cm.

In order that a work test should be judged as maximal, it was required that the heart rate at end of work was at least 175 beats per min and that, on close supervision, the subject was deemed to be so exhausted as not to be able to continue to work or to maintain the prescribed rate of revolutions (60 r.p.m.). In no case was it necessary to reject a test. During the test the subject was encouraged to continue work until complete exhaustion. Even if the expected work time, which was unknown to the subject, had been attained, the encouragement continued with unchanged intensity.

Table II. *Heart rate at termination of work, total work time, and physical work capacity ($W_{max\ 6\ min}$) obtained from the various work tests*

Work test	Final heart rate, beats × min^{-1} $\bar{x}$	S.D.	Range	Work time, min $\bar{x}$	S.D.	Range	$W_{max\ 6\ min}$, kpm × min^{-1} $\bar{x}$	S.D.	Range
Preliminary test (type *b*)	193.2	7.74	175–210	11.24	6.10	2.5–20.3	1 603	256	1 174–2 085
Type a_I[a]	190.5	7.84	175–200	6.54	1.64	4.4–10.7	1 616	241	1 180–2 002
Type *b*	195.7	8.01	185–218	22.06	1.49	19.2–25.1	1 649	261	1 186–2 114
Type a_{II}[a]	190.7	7.66	176–204	5.84	1.00	4.1– 7.7	1 610	256	1 122–2 074
Determination of $\dot{V}_{O_2max}$	191.3	7.66	182–208	16.26	1.19	14.5–19.7			
Type a_{II}[b]	190.4	7.56	176–200	5.79	1.05	4.1– 7.7	1 607	270	1 122–2 074
Type c[b]	192.2	6.81	185–208	24.72	3.67	19.8–31.3	1 597	268	1 073–2 083

[a] I = first series, II = second series.
[b] $n = 24$.

Four variants of work tests were used:

(*a*) A work test ad modum Tornwall (at constant load), for which the result was calculated in accordance with equation (2). This test is called test *a* in the following.

(*b*) A work test in which the load was raised by 200 kpm × min^{-1} after 12 and again after 18 min (and, if necessary, additional increases by 200 kpm × min^{-1} every 6th minute) as shown in Fig. 1. This test is called test *b* in the following. From the result of this test $W_{max\ 6\ min}$ was estimated as follows. According to equation (2) 12 min at load N is equivalent (in respect of $W_{max\ 6\ min}$) to t_1' min at load $N+200$, where

$$\log t_1' = \log 12 - 4.959\ [\log (N+200) - \log N] \quad (3)$$

To t_1' was added the time, t_1 (= 6 min), worked by the subject at load $N+200$ and, analogously, the work time, t_2', at load $N+400$ was calculated which corresponded to $(t_1'+t_1)$ min at load $N+200$:

$$\log t_2' = \log (t_1'+t_1) - 4.959\ [\log (N+400) - \log (N+200)] \quad (4)$$

To t_2' was added the time, t_2, worked by the subject at load $N+400$. (If the load was raised three times, an additional recalculation and addition were made.) $W_{max\ 6\ min}$ was obtained from the equation

$$\log W_{max\ 6\ min} = \frac{\log (t_h' + t_h) - \log 6}{4.959} + \log [N + (h \times 200)] \quad (5)$$

where h = number of increases of load.

The manner of recalculation and addition of the work times is illustrated in Fig. 2.

(*c*) A work test in which the load was initially 300 or 600 kpm × min^{-1} but was raised by 300 kpm × min^{-1} every 6th minute as shown in Fig. 1. This test is called test *c* in the following. The result was calculated analogously to that for test *b*:

$$\log t_1' = \log 6 - 4.959\ [\log (N+300) - \log N] \quad (6)$$

$$\log t_2' = \log (t_1'+6) - 4.959\ [\log (N+600) - \log (N+300)] \quad (7)$$

Further recalculations were made analogously to equations (6) and (7) until $W_{max\ 6\ min}$ could be obtained from the equation

$$\log W_{max\ 6\ min} = \frac{\log (t_h' + t_h) - \log 6}{4.959} + \log (N + h \times 300) \quad (8)$$

(*d*) A work test during which maximal oxygen uptake was determined. After a 10-min warm-up at 50 % of the maximum load which the subject was calculated to sustain for 6 minutes ($W_{max\ 6\ min}$) the load was raised to $W_{max\ 6\ min} - 50$ kpm × min^{-1}. After 3 minutes at the higher load a mouthpiece was inserted and, after an additional minute, the collection of expired air (45-sec portions) in Douglas bags started. Duplicate analyses were made of the samples by the Haldane technique

(precision $\sqrt{(\Sigma d^2)/2n} = 0.025$ vol % O_2)

$\dot{V}_{O_2max}$ was indicated as the highest value of oxygen uptake obtained for each subject.

EXPERIMENTAL PROCEDURE

At a preparatory visit the subject was given a general examination comprising, *inter alia*, heart-lung radiogram, ECG and physical examination, and a work test of type *b* in which the starting load for all subjects was 1 400 kpm × min^{-1}.

In a first series a work test of type *a* and a work test of

Table III. *Differences and relationships between the work tests*

Work test x_1	x_2	n	$d_{x_1-x_2}$ (kpm × min^{-1})	S.D.$_d$[a] (kpm × min^{-1})	r	s_e[b] (kpm × min^{-1})	Regression equation
Type a_I[c]	Type b	27	−32.8[d]	68.5	0.966	63.6	$x_1 = 0.892\ x_2 + 145$
Type a_I	Type a_{II}	27	6.3	62.0	0.971	59.0	$x_1 = 0.953\ x_2 + 145$
Type a_{II}	Type c	24	10.0	86.0	0.948	87.7	$x_1 = 0.953\ x_2 + 85$
Type a_{II}	$\dot{V}_{O_2max}$	27			0.881	118.0	$x_1 = 445.9\ x_2 + 81$
		27			0.881	0.23[e]	$x_2 = 0.00174\ x_1 + 0.62$

[a] $S.D._d = \sqrt{\frac{\Sigma(d-\bar{d})^2}{n-1}}$

[b] s_e = standard deviation of residuals.

[c] I = first series, II = second series.

[d] $p < 0.05$.

[e] $1 \times \text{min}^{-1}$.

type *b* were performed. On the basis of the results from the test at the preparatory visit the load in test *a* was so chosen that the subject was expected to be exhausted after 6 min, and the starting load in test *b* so that the subject would be exhausted after 21 min. (The loads were, however, rounded off to the nearest 50 kpm × min^{-1}.) The two tests were performed at one week's interval and in random order.

In a second series 2–4½ months after the first, a work test of type *a* was again carried out at the load (rounded off to the nearest 50 kpm × min^{-1}) for which the expected maximal work time was 6 min, and the work test in which maximal oxygen uptake was determined was performed. The tests were executed in random order and with at least 3 days' interval (3–14 days).

In a third series, 2–55 days after the second, test *c* was carried out with starting load 300 (or 600) kpm × min^{-1}. Owing to temporary illness, 3 subjects did not perform this test.

Means and standard deviations for the remaining 24 subjects have been reported earlier (5).

RESULTS

Table II shows the mean, standard deviation and range for final pulse rate, actual work time and $W_{max\ 6\ min}$ calculated from the various tests. In Table III the various estimates of $W_{max\ 6\ min}$ are compared, and it will be seen that the differences in mean values are small. Only in one case is the difference significant ($p < 0.05$).

The covariation between the different estimates of $W_{max\ 6\ min}$ is very high. In all cases r is 0.95 or higher (see Table III).

For test *a* the test–retest reliability was high (r = 0.97) although 3 months had elapsed between test and retest.

The relation between maximal oxygen uptake and $W_{max\ 6\ min}$, calculated from test *a*, was high ($r = 0.91$, $p < 0.001$), and with maximal oxygen uptake as dependent variable s_e amounted to 0.234 l × min^{-1} (6.7%).

DISCUSSION

The result of test *b* was significantly higher (33 kpm × min^{-1}) than that of test *a*. Correcting the result with regard to the mean difference, the standard error[1] in estimation of the result of test *a* from the result of test *b* was 68.5 kpm × min^{-1}, which may be compared with the standard error (62.0 kpm × min^{-1}) obtained when the result was estimated from the result of the second series with test *a*. The comparison is, however, not altogether fair as a considerably longer time (2–4½ months) had elapsed between the two tests of type *a* than between the first test of type *a* and the type *b* test (one week). Probably the difference in standard error would have been greater if the time between the tests had been the same. The observation that the error tends to be greater when the estimate is based on a test with duration about 22 min than on a test with duration about 6½ min is in accordance with Tornvall's ob-

[1] $\sqrt{\frac{\Sigma(d-\bar{d})^2}{2(n-1)}}$

servation that the uncertainty is greater at work times exceeding 12 min.

If the result is not corrected for the mean difference, the standard error[1] will be 76.2 kpm $\times$ min^{-1}. The results can, of course, also be corrected according to the regression equation (Table III), this leads to a standard error of the same order of magnitude (63.6 kpm $\times$ min^{-1}).

It cannot be asserted that in all contexts test *b* can be used instead of test *a* with a work time close to 6 min. But for the examination of draftees the advantage of, if necessary, raising the load after 12 and 18 min instead of testing on another day and at a more suitable load should more than outweigh the slight uncertainty of the result. The procedure has implied that the proportion of draftees with work times longer than 18 min has been reduced from 9% to below 3%.

In the present study the work times in test *b* varied between 19.2 and 25.1 min, so that no major conclusions can be drawn concerning the outcome of the test if carried out at a load which would have to be raised more than twice.

Comparison of the results from tests *c* and *a* shows that $W_{max\ 6\ min}$ can be estimated also from the former. This is an advantage, as one can then obtain four ordinary measures of physical working capacity from a single work test, i.e., in addition to $W_{max\ 6\ min}$, also W_{170}, HR_{900} and the maximal oxygen uptake ($\hat{V}_{O_2max}$) estimated from the pulse rate. A more important advantage is that, in the same way as in testing with W_{170}, one can follow the change of blood pressure, ECG etc. on gradual raising of the load, but, in contradistinction to the normal practice in the W_{170} test, by continuing to exhaustion or until the test must be stopped for reasons of safety, one obtains a more reliable estimate of the subject's maximal physical working capacity (or the highest load or pulse rate the subject can sustain without any untoward reactions).

The calculation of $W_{max\ 6\ min}$ may seem complicated, but tables have been drawn up from which $W_{max\ 6\ min}$ can be directly read both for tests of type *a* and for tests of types *b* and *c*. It would require too much space to reproduce these tables in this context, but Table IV may be of some assistance in conjunction with test *c*. It shows the calculated time, t'_h, to be added to the time worked by the subject at the final load for different initial loads and for varying number of increases of load. It will be seen from the table that, when the load has been raised several times, the work at the first loads has little significance for the estimate of $W_{max\ 6\ min}$. If the subject stops after 3 min at 1 500 kpm $\times$ min^{-1}, $t'_h + t_h$ will be 5.526, 5.524, 5.461 or 4.985 min depending on whether the initial load was 300, 600, 900 or 1 200 kpm $\times$ min^{-1}, which implies that $W_{max\ 6\ min}$ is 1 475.5, 1 475.4, 1 471.5 and 1 444.6 kpm $\times$ min^{-1} respectively.

Table IV. *Time in minutes to be added to the work time on the final load, when estimating $W_{max\ 6\ min}$ from work test of type c*

Initial load	Final load, kpm $\times$ min^{-1}					
(kpm $\times$ min^{-1})	600	900	1 200	1 500	1 800	2 100
300	0.123	0.830	1.639	2.526	3.450	4.402
600		0.804	1.632	2.524	3.449	4.402
900			1.440	2.461	3.426	4.390
1 200				1.985	3.232	4.300
1 500					2.429	3.926
1 800						2.795

The test-retest reliability has also been tested in a field study of screening character. As the initial load in all cases was 1 400 kpm $\times$ min^{-1} the test for those who were exhausted within 12 min was of type *a*, while the test for the remainder was of type *b*, since the load was raised by 200 kpm $\times$ min^{-1} at 12 min and if necessary, also after 18 and 24 min. Even in this non-ideal situation the reliability was found to be satisfactory ($r = 0.90$, $s_e = 84.8$ kpm $\times$ min^{-1}, $n = 83$).

In another field study, likewise of screening character, a combination of tests *a* and *b* (initial load 1 400 kpm $\times$ min^{-1} in all cases in the same way as above) was compared with a work test of type *c*. With test *c* as independent variable the correlation was of the same order as in the laboratory study, whereas the standard error was rather higher ($r = 0.90$, $s_e =$ 105.5 kpm $\times$ min^{-1}, $n = 107$). On this occasion the lactic acid level in the blood was determined at the end of test *a* (or *b*) and the mean was found to be 12.2 mmol $\times$ l^{-1}, S.D. 2.5 mmol $\times$ l^{-1}.

[1] $\sqrt{\frac{\Sigma d^2}{2n}}$

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