Maximal short term exercise capacity in healthy subjects aged 15-70 years

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Summary
1. Fifty males and 50 females, 15-71 years of age, exercised maximally for 30 s on an isokinetic ergometer at a pedalling frequency of 60 rev./min. Results were compared with maximal oxygen uptake ($\dot{V}O_{2,\text{max}}$) obtained in a progressive incremental exercise test.

2. Total work in 30 s was higher in males than females, declined linearly by about 6% per decade of age ($r = -0.65$), and was related closely to height ($r = 0.75$) and to lean thigh volume estimated anthropometrically ($r = 0.84$). A close association with vital capacity ($r = 0.86$) was also found that accounted statistically for the combined effects of age and height.

3. The percentage decline in power during 30 s (fatigue index) was lower in subjects reporting greater leisure activity.

4. A close relationship was found between total work in 30 s and $\dot{V}O_{2,\text{max}}$ ($r = 0.86$), with vital capacity and leisure activity exerting additional influences on $\dot{V}O_{2,\text{max}}$. ($P < 0.001$; multiple $r = 0.93$).

5. The well-established reduction with age in $\dot{V}O_{2,\text{max}}$ is associated with an apparent parallel reduction in the power output capacity of large muscle groups recruited in heavy dynamic leg exercise.

Key words: ageing, body size, exercise, fatigue, leisure activity, oxygen uptake, thigh volume.

Introduction
The major factors that influence maximum aerobic power ($\dot{V}O_{2,\text{max}}$) in an untrained population have been recognized for many years as being those of gender, age and body size [1-4], with other factors playing a less important role. Recently attention has been drawn to other indices of maximal exercise performance, such as the maximum power developed in short term, theoretically 'anaerobic' exercise [5], but the values to be expected in normal subjects of different sexes, age and size have not been as well defined as for $\dot{V}O_{2,\text{max}}$. The studies described in the present paper provide such values, and in particular focus on the influence of age on indices of maximal exercise performance.

There are a number of physiological changes that accompany the steady fall in aerobic exercise capacity that occurs with age [6]. Central mechanisms influencing oxygen transport, such as the maximum cardiac output and heart rate [2, 6-8], and pulmonary gas exchange function [9], decline steadily after the third decade. Also there are decreases in total muscle mass and the number of functioning motor units [10-12]; this is associated with histochemical and histological evidence of denervation in ageing muscle and a reduction in muscle strength that accelerates after the age of 65 [10-13]. Although the age-related changes in muscle structure and function and in central oxygen delivery mechanisms appear to occur in parallel and are of similar magnitude [14], it remains to be determined if the same factors underlie these changes, or whether they occur independently.

Cross-sectional and longitudinal studies of healthy subjects have suggested that the rate of decline in aerobic exercise capacity with increasing
years is influenced by the level of habitual physical activity, with more active subjects exhibiting a slower rate of decline than sedentary subjects [6, 15, 16]. Whether the effects of habitual physical activity are mediated through the maintenance of cardiac function or by lessening the decline in muscle function is not established. In part, the difficulty in answering these questions is related to uncertainty as to the expected values for maximal muscle power in healthy subjects of various ages. The present study employed an isokinetic cycle ergometer [17] to measure power output and related variables during a brief period of maximal exercise in healthy subjects aged 15–71 years. As the test lasted 30 s only, central oxygen delivery mechanisms theoretically should play relatively little part in meeting the energy requirements of the exercise. In addition to providing data related to normal values of maximum exercise capacity the study compared results obtained with this procedure, with measurements of maximal oxygen intake in a standard progressive incremental exercise test, to examine possible associations between aerobic performance and maximal glycolytic ('anaerobic') capacity.

Methods

The subjects were 100 healthy volunteers, 50 males and 50 females, who were recruited to provide a wide distribution of ages (from 15 to 71 years, Table 1), and of height (males 165–194 cm; females 152–176 cm). Recruitment was by advertisement in local publications and a local radio station; responders were asked their age and height and recruited into the study if a vacancy existed in their respective category; other exclusion criteria included competitive athletes (past or present), and history of serious cardiac or pulmonary disease. At the time of the study spirometric evidence of significant airflow obstruction (> 2 SD below predicted values), abnormal resting electrocardiograph, medications known to influence exercise performance, and systemic hypertension (resting blood pressure of 150/90 mmHg or above) constituted additional exclusion criteria. Subjects gave signed informed consent after description of the procedures and possible risks and the study was approved by the institution's ethics committee. No remuneration was offered to subjects.

A smoking history and information on occupational physical activity and activity during leisure hours was obtained by questionnaire. There were 50 life-long non-smokers; 31 subjects had stopped smoking for at least a year before; 13 smoked less than 15 cigarettes per day, and six smoked more than 15 cigarettes per day. Occupational activity was categorized in three grades: sedentary (54 subjects), occupations requiring some standing and walking (30) and those requiring constant activity (10); in six subjects occupational activity was not categorized. Leisure activity was classed into four grades according to the hours per week spent in recreational activity (1, comprising 26 subjects, exercised for less than 1 h; 2, 42 subjects, for 1–3 h; 3, 23 subjects, for 3–6 h; and 4, nine subjects, exercised for more than 6 h); 'activity' was defined as any exertion associated with at least a doubling of the resting metabolic rate [18]. Smoking, occupational and leisure activities were similar in males and females.

Measurements of vital capacity (VC) and the forced expired volume in 1 s (FEV₁) were obtained with a calibrated dry spirometer (Vitalograph); the best of three attempts was recorded for both measurements.

<table>
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<th>Age (years)</th>
<th>Males</th>
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<tr>
<td></td>
<td>Height (cm)</td>
<td>Weight (kg)</td>
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Subjects performed two exercise tests on different days: an incremental multistage progressive exercise test and a 30 s maximal cycling test on an isokinetic ergometer. The incremental test was always carried out first, partly to screen the population for untoward effects of exercise: two older subjects were excluded on the basis of electrocardiographic changes consistent with coronary artery disease.

The progressive multistage exercise test [18] was performed on a calibrated stabilized load cycle ergometer (Elma EM 370); the procedure is described in a separate report [19] in which the submaximal and maximal measurements are presented. In brief, the initial power output was 100 kpm/min (16.3 W) and the power output was increased by 100 kpm/min at the end of each minute until the subject could no longer maintain a required pedal frequency. The subject breathed through a low resistance, low dead space valve, inspired ventilation was measured by dry gas meter, and expired gas was analysed for oxygen and carbon dioxide by a Perkin-Elmer MGA 1100 respiratory mass spectrometer. Measurements were averaged every 15 s and the mean of the highest three measurements of oxygen uptake was taken as the subject's capacity ($\bar{V}\text{O}_2 \text{max}$). Although a plateau of $\bar{V}\text{O}_2$, with $\bar{V}\text{O}_2$ being maintained within ±5% for 1 min at maximum effort, was usually obtained, this was not a requirement for the measurement.

After the incremental exercise test the isokinetic cycle ergometer test was explained to the subject and a practice test was performed.

On the second occasion lean thigh volume was estimated from anthropometric measurements [20], and the subject carried out a 30 s cycling test on an isokinetic cycle ergometer. The ergometer, and procedure, are described in detail elsewhere [17]. The velocity of pedalling was controlled to a predetermined rate by a 3 h.p. motor, and an electrical speed controller. The pedalling rate in the present study was controlled at 60 rev./min, chosen because it is the velocity at which most exercise tests are carried out [18]. The subject pedalled with maximal effort and the torque exerted on the pedals was recorded via strain gauges bonded to the pedal cranks and connected to a multichannel recorder and computer through a slip ring and a Wheatstone bridge circuit.

The ergometer was calibrated before each test. The optimal saddle height was selected for the subject and feet were secured to the pedals by toe clips and straps. A webbing harness around the hips prevented lateral and forward movement and ensured that the major contribution to force output was from the quadriceps muscles. The subject was instructed to exert maximal effort; constant encouragement was given to the subject during the test, with instructions not to grip the handlebars tightly and to breathe regularly. Heart rate and the electrocardiograph were monitored throughout the test and during recovery. There were no untoward sequelae.

The output from the strain gauges was sampled at 10 ms intervals by a laboratory computer (PDP 11-03, Digital Equipment Corp.) that performed integration with respect to time. Measurements were obtained in each subject of peak instantaneous power, average power and work for each pedal revolution, and total cumulative work during the test. All subjects showed a gradual and smooth decline in power during the 30 s test; the decline in average power by the end of the test was expressed as a percentage of the maximum power achieved during the first few pedal strokes (fatigue index, FI) [17]. Our experience with this test in healthy subjects [21] and patients with coronary artery disease (unpublished work) has indicated that the measurements are repeatable in a given subject with a coefficient of variation less than 10%, and that there is no significant effect of habituation.

**Results**

Performance in the 30 s test could be characterized equally well by all three variables, maximum peak instantaneous power ($W_{\text{inst}}$), maximum average power ($W_{\text{av}}$) and the total work achieved in the 30 s of the test ($W_{\text{tot}}$), in that the correlation coefficients between them were in excess of 0.98.

**Effects of age**

Male and female subjects $W_{\text{inst}}$ and $W_{\text{av}}$ showed a decline with age that amounted to about 6% for each decade. For maximum peak power, mean values in the 15-24 years decade were 1037 W in males and 661 W in females, declining to 760 W and 466 W respectively in the subjects over 55 years. Maximum average power was 656 W and 404 W respectively, falling to 455 W and 282 W for the same age groups. Similarly, the total cumulative work was 17.8 kJ and 10.6 kJ with a decline to 12.0 kJ and 7.4 kJ (Fig. 1). Thus the percentage decline with age for all three variables was almost identical, and similar for males and females. Total work was statistically the variable most closely related to age ($r = -0.65$). Values for all three variables in females were about two-thirds of the values obtained in males (Fig. 1). The following regression equations express the
influence of age on these three variables in the two sexes:

**Males**

\[ W_{\text{inst.}} = 1222 - 7.3 \text{ (age) W} \]  
(SEE 152, \( r = -0.59 \))

\[ W_{\text{av.}} = 770 - 4.7 \text{ (age) W} \]  
(SEE 102, \( r = -0.58 \))

\[ W_{\text{tot.}} = 20.8 - 0.137 \text{ (age) kJ} \]  
(SEE 2.30, \( r = -0.66 \))

**Females**

\[ W_{\text{inst.}} = 780 - 5.0 \text{ (age) W} \]  
(SEE 91, \( r = -0.64 \))

\[ W_{\text{av.}} = 486 - 3.1 \text{ (age) W} \]  
(SEE 62, \( r = -0.61 \))

\[ W_{\text{tot.}} = 12.7 - 0.085 \text{ (age) kJ} \]  
(SEE 1.41, \( r = -0.66 \))

where age is in years.

*Effects of body size*

In both females and males, the power variables \( W_{\text{inst.}} \) and \( W_{\text{av.}} \) and also \( W_{\text{tot.}} \) showed strong correlations to parameters of body size; height \((r = 0.75\) for all variables) was more closely related to all three variables than weight \((r = 0.66\).

Analysis of covariance showed that significant \((P < 0.001)\) effects of age and sex remained even when height or weight was taken into account. The regression equations linking these variables for the total population were:

\[ W_{\text{inst.}} = 8.2 \text{ (ht.)} - 5.2 \text{ (age)} - 251 \text{ (sex)} - 310 \text{ W} \]  
(SEE 119, \( r = 0.87 \))

\[ W_{\text{av.}} = 5.0 \text{ (ht.)} - 3.4 \text{ (age)} - 160 \text{ (sex)} - 175 \text{ W} \]  
(SEE 81, \( r = 0.87 \))

\[ W_{\text{tot.}} = 0.125 \text{ (ht.)} - 0.097 \text{ (age)} - 4.5 \text{ (sex)} - 3.14 \text{ kJ} \]  
(SEE 78, \( r = 0.89 \))

\[ W_{\text{tot.}} = 0.108 \text{ (wt.)} - 0.117 \text{ (age)} - 4.4 \text{ (sex)} + 11.5 \text{ kJ} \]  
(SEE 1.80, \( r = 0.90 \))

where height \((\text{ht.})\) is in cm, weight \((\text{wt.})\) in kg, age in years and sex is coded 0 for males and 1 for females.

Lean thigh volume (sum of both legs) was closely related to maximum peak power \((r = 0.81)\), maximum average power \((r = 0.80)\) and total work \((r = 0.84)\) (Fig. 2); the regression equation for this last relationship was:

\[ W_{\text{tot.}} = 1.45 \text{ (tv)} + 1.36 \text{ kJ} \]  
(SEE 2.22, \( r = 0.84 \))

where lean thigh volume for both legs \((\text{tv})\) is expressed in litres. Similar significant relationships were found for males and females separately.

Analysis of covariance showed that when the relationship between the power variables and thigh volume had been taken into account, an age effect did not remain.

*Effects of habitual activity*

The occupational level and the time spent in active leisure pursuits did not have a significant
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Fig. 2. Total work done in 30 s in males (●) and females (○), related to lean thigh volume, average of the two legs, estimated from anthropometric measurements.

Effect on \( W_{\text{inst}} \), \( W_{\text{av}} \), or \( W_{\text{tot}} \), when height, weight and age had been entered into an analysis of covariance.

Fatigue index

In contrast to power variables and the total work, the fatigue index was not related to age, height or weight. The average fatigue index for \( W_{\text{inst}} \) and \( W_{\text{av}} \) over the 30 s of the test was 26 ± 10.0% in males and 30 ± 9.7% for females (not significant). A weak negative correlation (\( r = -0.30 \)) was found between the fatigue index and leisure activity grade, suggesting a possible association between these two variables (\( P < 0.001 \)). There was no significant relationship between the fatigue index and maximum power variables.

Comparison of 30 s performance with \( VO_2 \) max.

Significant relationships (\( P < 0.001 \)) were obtained between the two power variables and total work and \( VO_2 \) max. measured in the incremental exercise test (\( r = 0.89 \) for all three variables) (Fig. 3). There were significant relationships between \( VO_2 \) max. and height (\( r = 0.78 \)), weight (\( r = 0.65 \)) and lean thigh volume (\( r = 0.79 \)). Other variables that were significantly related (\( P < 0.001 \)) to both power variables, to total work (\( r = 0.84 \)) and to \( VO_2 \) max. (\( r = 0.86 \)) were the VC and FEV1; these variables statistically took into account the combined effects of height, age and sex.

Multiple stepwise regression analysis was used to examine associations between measurements of body size, maximum power variables and other variables and \( VO_2 \) max. The total work was the variable most closely related to \( VO_2 \) max. (\( F = 63.9, P < 0.0001 \)), followed by VC (partial \( F = 26.2, P < 0.001 \)) and leisure activity (partial \( F = 19.3, P < 0.001 \)). The multiple regression equation for this relationship was:

\[
VO_2 \text{max.} = 0.123 \times (W_{\text{tot.}}) + 0.30 \times (VC)
+ 0.17 \times \text{(leisure)} - 0.898 \text{ l/min}
\]

(see 0.415, \( r = 0.93 \))

Thus only 13% of the variance (\( r^2 = 0.87 \)) in measurements of \( VO_2 \) max. was left unexplained once the total work, VC and leisure activity had been entered into the stepwise regression procedure. A similar expression was derived where age, sex, height and weight replaced the constant for VC:

\[
VO_2 \text{max.} = 0.131 \times (W_{\text{tot.}}) + 0.016 \times (ht.)
- 0.008 \times \text{(age)} - 0.059 \times \text{(sex)} + 0.007 \times \text{(wt.)}
+ 0.145 \times \text{(leisure)} - 2.44 \text{ l/min}
\]

(see 0.458, \( r = 0.92 \)).

Discussion

The present study employed a recently developed isokinetic cycle ergometer that enables power and
fatigue to be measured precisely during dynamic cycling exercise [17]. The results provided information regarding the factors that influence muscle power in healthy subjects, the effects of ageing, and associations between maximal short-term muscle power and maximal exercise aerobic capacity ($V_{O_2\text{max}}$).

The measurements were made in males and females, selected to provide a wide distribution of age and height. Although the study may be criticized on the grounds that the sample size was too small to be representative of the population, we sought to minimize this effect by selecting for as even a distribution as possible for age and height. The measurements made in the study to characterize the population were comparable with established normal values for pulmonary function data [22] and maximal exercise test results [6, 7, 19, 23].

Although the majority of studies that have investigated maximal exercise capacity have been concerned with aerobic power as reflected in $V_{O_2\text{max}}$, recently there has been an increased interest in maximal short-term or anaerobic power, in which the duration of exercise is 30 s or less. In meeting the demands of maximal exercise for a short time, there is less reliance on muscle oxygen delivery than in exercise of lesser intensity or longer duration, and large increases in muscle [24] and plasma [21] lactate concentrations are found. Several studies have employed the Wingate test [25], in which the subject pedals as fast as possible on a mechanically braked ergometer; after maximal pedal velocity is reached a standardized resistance is imposed; during 30 s the pedal velocity is monitored and declines progressively; power is calculated from the resistance and the number of revolutions of the flywheel during each 5 s of the test. Although the methods used in the present study are more complex, they have the advantages of measuring torque directly and at a constant velocity; thus no assumptions have to be made regarding changes in frictional and inertial forces during the procedure. The relationship between peak power and crank velocity is a parabola, with a peak of optimal velocity between 120 and 160 rev./min [21]; although our choice of 60 rev./min may not have represented the cycling frequency required for our subjects’ maximum power, it is the frequency associated with the least fatigue and subjective stress [21], and also that employed in most cycle ergometer tests [18]. Furthermore, it has been our experience that elderly or infirm subjects find difficulty in pedalling at the very high frequencies that are required in the Wingate test. The Wingate test was not used in a study comparable with the present one (O. Bar-Or, personal communication), but comparison of our results in the younger subjects with those reported for the Wingate test [24, 25] suggests that the average power measurements are similar.
As in previous studies that used an isokinetic ergometer in healthy young subjects [21], we found close relationships between the maximum peak and average power, and the total cumulative work indicating that any one of the three could be used as an index of maximal performance during this type of exercise, but for most relationships the total cumulative work during the test gave the least variation. Total work was higher in males (mean 15.6 kJ) than females (9.1 kJ) and showed a gradual decline with age that on average amounted to 6% per decade of age in both sexes (Fig. 1).

At any given age there were associations between the power variables and height and, less significantly, weight. For subjects of given size, age was significantly related to power variables, but when thigh volume measurements were used in an analysis of covariance, age was not found to exert an independent effect. The estimate of lean thigh volume from anthropometry [20] is potentially subject to error, but it is of interest that it was the measurement to which power was most closely related. This finding is consistent with previously established relationships between maximum power during cycling and the size of muscles [5, 21]. Although the small age-related decline in lean thigh volume ($r = -0.25, P < 0.01$) may thus contribute to the reductions in power, this decline in our subjects was not uniform with age. When data in males and females were combined, lean thigh volume (sum of both thighs) was found to fall by 11% between age 20 and 30 years (from 8.66 litres to 7.67 litres); a further 8% between 30 and 40, to 6.94 litres, but no further significant reductions occurred, mean values being 6.78 litres at age 50 and 6.9 litres at 60 years. As discussed below, changes in muscle function with age are only partly related to size, several other factors making significant contributions. Aniansson et al. [13] showed that reductions with age in muscle strength and the ability to perform a step test correlated with reductions in body cell mass and muscle fibre area. Although these workers did not find histological evidence of muscle degeneration, Grimby et al. [26] found changes consistent with denervation and re-innervation in 80 year-old subjects; because falls in lean body mass were more marked than in fibre area, they suggested that a loss of fibres also occurred in old age.

Whereas the maximal power variables measured during the isokinetic cycle ergometer test appear to reflect mainly muscle size, the relative extent to which power declines during the 30 s (fatigue index) was found to be unaffected by age and size; indeed the relationship between average thigh volume and fatigue was positive, suggesting that the larger the thigh muscle volume the greater the relative fatigue during the test. The explanation appears to lie in the fact that subjects with larger thighs achieved the higher maximum peak power; although the decline from these maximum values was greater, the total work accomplished in the 30s (a composite function of both maximum power and the fatigue index) is still greater in subjects with greater muscle mass.

The finding in the present study of a decline with age in the peak power and total work in 30 s, without a significant change in the fatigue characteristics, may indicate a relative preservation of oxidative fatigue-resistant muscle fibres in older subjects. This hypothesis is consistent with the finding in several studies of a reduction in the size and number of fast twitch type 2 fibres with age [2, 4, 10, 27]. Such age-related changes may be due to the motoneuron dysfunction shown by Campbell et al. [12] to occur with age.

Although the measurement of $V_{O_2 \text{max}}$ conventionally is used to assess aerobic power, whereas the total work in 30 s mainly assesses the muscles’ maximal glycolytic, or ‘anaerobic’, capacity, a close relationship was obtained between the two measurements. Also the two indices appeared to decline with age at similar rates. The high correlation between total work and $V_{O_2 \text{max}}$ suggests that there are common factors contributing to both measures; taken with the relationship between thigh volume and $V_{O_2 \text{max}}$. this finding suggests that in the average population the size of muscles and their capacity to generate power are important factors contributing to the maximal aerobic power in exercise [28]. However, if we had included well-trained endurance athletes in our population their $V_{O_2 \text{max}}$ would be high in relation to the maximum isokinetic power (Fig. 3) [17]. Gollnick et al. [29] showed specific training effects in terms of muscle enzyme activities in athletes trained for different events that provide a biochemical basis for the fatigue resistance and high $V_{O_2 \text{max}}$ of endurance athletes.

A number of studies have shown that, for any given age and size, active individuals tend to have a higher $V_{O_2 \text{max}}$ than inactive subjects [30]. Furthermore, longitudinal studies have established that the decline in $V_{O_2 \text{max}}$ with age is less in the active than inactive [15, 31, 32]. In the present study a simple categorization of subjects according to weekly leisure activity hours had a positive influence on $V_{O_2 \text{max}}$ and was associated with a reduction in fatigue during the 30s maximum cycling test. Thus these findings raise the possibility that the maintenance of muscle quantity and quality are both important in the maintenance
of $\dot{V}O_{2,max}$ with increasing age. Although the well-established linear decline in maximum cardiac frequency with age [7] has been used as an indication that the fall in $\dot{V}O_{2,max}$ is determined by 'central' factors related to intrinsic myocardial properties [33], it may be argued that the function of muscles may be at least as important.

Our findings have implications for the maintenance of muscle size and function and of their aerobic power with age. It seems likely that subjects in active occupations will maintain muscle size and the muscle's aerobic capacity will be maintained by regular leisure activity. In addition, the possibility is raised that exercise carried out at any age may help to improve muscles' aerobic capacity and thus help to maintain $\dot{V}O_{2,max}$. Aniassson & Gustafsson [34] trained 1270 year-old subjects and showed increases in the area of type 2 fibres associated with improvements in muscle function. In spite of evidence of neurally mediated degeneration of muscle with age [12], muscle remains susceptible to improvement by training techniques.

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