Oxygen-Uptake (VO₂) Kinetics and Functional Mobility Performance in Impaired Older Adults

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Background. Measures of maximal oxygen uptake (VO₂max) are limited in disabled older adults, and measures of submaximal oxygen uptake (VO₂) may better predict functional mobility limitations. These measures may include oxygen-uptake kinetics at the onset of submaximal exercise or during recovery. We sought to determine whether the lag in oxygen uptake at the beginning of exercise (oxygen deficit) and excess oxygen uptake above rest following exercise (excess postexercise oxygen consumption) (a) predict physical performance in impaired older adults with decreased aerobic function, and (b) predict physical performance better than peak VO₂.

Methods. Two groups of community-dwelling volunteers aged 65 or older were recruited according to their performance on a maximal graded exercise test. Using the Social Security Administration criterion of disability of a peak VO₂ ≤ 18 ml/kg/min, we compared the performance of an impaired aerobic capacity group at a peak VO₂ < 18 ml/kg/min (Impaired, n = 20, mean ± SEM age 82 ± 1 years) with an unimpaired group at Peak VO₂ > 18 (Unimpaired, n = 21, mean ± SEM age 76 ± 1 years).

Results. The mean ± SEM peak VO₂ was 58% lower in the Impaired (14 ± 1 ml/kg/min) than the Unimpaired (24 ± 1 ml/kg/min) adults. The time constant for oxygen deficit, tCd, was more than twice as high in the Impaired than the Unimpaired (p < .05), and the time constant for excess postexercise oxygen consumption, tEPOC, tended to be higher in the Impaired than the Unimpaired (by 43%, p = .09). Measures of submaximal oxygen-uptake kinetics were as strong or more strongly predictive of functional mobility performance than peak VO₂ in both Unimpaired and Impaired older adults. The major predictor of functional performance for the Unimpaired was a measure of oxygen deficit accruing during exercise (tD,imp), and for the Impaired, it was a measure of oxygen debt during recovery, tD,pm.

Conclusions. Measurement of submaximal oxygen-uptake kinetics may provide a more practical and relevant assessment of deconditioning in frail older adults, and may eventually supplant maximal (peak) oxygen uptake as a predictor of functional disability in older adults.

Impairment in daily mobility activities, such as walking, is common in older adults, with as many as one half of community-dwelling men and women by age 80 years reporting difficulty, need for assistance, or the use of a walking device in walking a quarter mile (1). While strength and balance are often major contributors to mobility limitations, cardiorespiratory fitness, often measured as maximal oxygen uptake (VO₂) at peak oxygen uptake (VO₂peak) or peak oxygen uptake (VO₂max), may better predict functional mobility limitations. These measures may include oxygen-uptake kinetics at the onset of submaximal exercise or during recovery. We sought to determine whether the lag in oxygen uptake at the beginning of exercise (oxygen deficit) and excess oxygen uptake above rest following exercise (excess postexercise oxygen consumption) (a) predict physical performance in impaired older adults with decreased aerobic function, and (b) predict physical performance better than peak VO₂.

Methods. Two groups of community-dwelling volunteers aged 65 or older were recruited according to their performance on a maximal graded exercise test. Using the Social Security Administration criterion of disability of a peak VO₂ ≤ 18 ml/kg/min, we compared the performance of an impaired aerobic capacity group at a peak VO₂ < 18 ml/kg/min (Impaired, n = 20, mean ± SEM age 82 ± 1 years) with an unimpaired group at Peak VO₂ > 18 (Unimpaired, n = 21, mean ± SEM age 76 ± 1 years).

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Conclusions. Measurement of submaximal oxygen-uptake kinetics may provide a more practical and relevant assessment of deconditioning in frail older adults, and may eventually supplant maximal (peak) oxygen uptake as a predictor of functional disability in older adults.
In patients with cardiovascular disease, the oxygen-uptake kinetics are slower (11), and the increase in oxygen deficit at the onset of exercise results in an increase in the oxygen debt during recovery from exercise (12). A time constant is calculated based on single exponential kinetics of oxygen uptake from the start of exercise until steady state achieved during a submaximal exercise. Similarly, a time constant is calculated during the recovery period after the submaximal exercise. In patients with congestive heart failure, both time constants, which are increased compared with controls (indicating a delayed response), predict cardiac capacity (11–13) and cardiac output (14) better than other submaximal exercise parameters (15). The time constants also are thought to predict congestive heart failure functional outcome, including survival (16) up to 10 years (17). Could this delay in oxygen-uptake kinetics be at least partly accountable for mobility limitations found in many older adults? More specifically, in disabled older adults, is either the oxygen deficit at onset of physical activity or the oxygen debt to be repaid during rest periods responsible for limitations in performance of certain tasks? Little data examine the role of oxygen-uptake kinetics at activity onset or during recovery from the activity as having a role in functional-mobility limitations in older adults.

For the present study, we sought to determine whether submaximal oxygen uptake kinetics (the oxygen deficit during activity and the oxygen debt to be repaid during rest) (a) predict physical performance in impaired older adults with decreased aerobic function, and (b) predict physical performance better than VO2max. We hypothesized that, compared with older adults without aerobic impairment based on measures of VO2peak, older adults with aerobic impairment have (a) slower oxygen-uptake kinetics, and (b) poorer functional mobility performance. In addition, we hypothesized that measures of submaximal oxygen-uptake kinetics would correlate more strongly with functional mobility performance than measures of VO2peak, i.e., VO2max.

METHODS

Subjects

Two groups of community-dwelling volunteers aged 65 or older were recruited according to their performance on a graded treadmill test to maximum exercise tolerance. Using the Social Security Administration criterion of disability of a VO2peak ≤ 18 ml/kg/min, we compared the performance of an impaired aerobic capacity group at a VO2peak < 18 ml/kg/min (Impaired, n = 20, mean ± SEM age 82 ± 1 years, mean ± SEM VO2peak 14.2 ± 0.5 ml/kg/min) with an unimpaired group at VO2peak > 18 (Unimpaired, n = 21, mean ± SEM age 76 ± 1 years, mean ± SEM VO2peak 24.4 ± 0.9 ml/kg/min) (see Tables 1 and 2). This criterion of 18 ml/kg/min is particularly relevant to the present study given recent findings that older adults with a VO2max < 18 ml/kg/min had greater self-reported functional difficulty than those with a VO2max > 18 ml/kg/min (3). Subjects were screened for the presence of recent myocardial infarction, exercise-induced angina, uncontrolled dysrhythmia, severe congestive heart failure, and the presence of a severe neurological or musculoskeletal conditions resulting in focal weakness or pain that precluded completion of the testing. Subjects were included with a number of chronic conditions, primarily chronic neurological or musculoskeletal conditions such as chronic arthritis or previous joint replacement. No subjects with active cardiopulmonary conditions (such as symptomatic, untreated congestive heart failure or chronic obstructive pulmonary disease) were included. To assess functional limitations in these 2 groups, subjects were asked about their self-reported difficulty/disability using the Established Populations for the Epidemiologic Study of the Elderly (EPESE) questionnaire (3,18), which includes activities of daily living (ADL) and mobility-relevant Rosow-Breslau and Nagi items (such as walking up and down a flight of stairs, walking one half mile, moving heavy objects, or carrying objects such as a bag of groceries). Subjects were allowed to take their normal medications the day of testing, which included antihypertensives and beta-blockers (4 in the Impaired group and 1 in the Unimpaired group).

Treadmill Tests

Subjects first acclimatized themselves to the treadmill and facemask used during the treadmill test. A 12-lead electrocardiogram and arm cuff blood pressure measurement were performed at rest and every 2 minutes and at 6 minutes postrecovery. During both rest and exercise periods, breath-by-breath ventilation (V̇E), oxygen uptake (VO2), and carbon dioxide produced (VCO2) were measured using a SensorMedics Vmax Cardiopulmonary Exercise System (Yorba Linda, CA).

Submaximal oxygen-uptake kinetics determination.—Subjects exercised at a submaximal load (1 mph [miles per hour], 0% grade) to determine their submaximal oxygen-uptake kinetics (VO2). Subjects stood on a platform immediately above the treadmill belt for 3 minutes to

### Table 1. Subject Characteristics

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Unimpaired</th>
<th>Impaired</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (No. of females)</td>
<td>21 (13)</td>
<td>20 (17)</td>
</tr>
<tr>
<td>Mean (± SEM) age (y)</td>
<td>76 (1)</td>
<td>82 (1)*</td>
</tr>
<tr>
<td>Age range (y)</td>
<td>69–83</td>
<td>68–91</td>
</tr>
<tr>
<td>Mean (± SEM) height (cm)</td>
<td>169 (2)</td>
<td>163 (2)</td>
</tr>
<tr>
<td>Mean (± SEM) weight (kg)</td>
<td>72 (3)</td>
<td>73 (5)</td>
</tr>
<tr>
<td>Mean (± SEM) body mass index (kg/m²)</td>
<td>26 (1)</td>
<td>27 (1)</td>
</tr>
<tr>
<td>Median Nagi score</td>
<td>0</td>
<td>4.0*</td>
</tr>
<tr>
<td>Median Rosow-Breslau score</td>
<td>0</td>
<td>2.5*</td>
</tr>
</tbody>
</table>

Note: *p < .05.

### Table 2. Mean (± SEM) Peak Oxygen Uptake, Oxygen Uptake, and Recovery Kinetics

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Unimpaired</th>
<th>Impaired</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak VO₂ (ml/kg/min)</td>
<td>24.4 (0.9)</td>
<td>14.2 (0.5)*</td>
</tr>
<tr>
<td>Time for oxygen deficit (tc deficit, s)</td>
<td>23.4 (3.1)</td>
<td>58.0 (9.3)*</td>
</tr>
<tr>
<td>Time for oxygen debt (tc EPOC, s)</td>
<td>40.1 (7.3)</td>
<td>57.1 (6.6)</td>
</tr>
<tr>
<td>VO₂ at 1.0 mph (ml/kg/min)</td>
<td>8.3 (0.9)</td>
<td>8.7 (0.4)</td>
</tr>
</tbody>
</table>

Notes: *p < .05. VO₂ = oxygen uptake; tc = time constant; EPOC = excess postexercise oxygen consumption.
determine their baseline oxygen consumption. Subjects then stepped off the platform onto the moving treadmill and performed a 6-minute constant load walk at 1 mph. Upon completion of the 6-minute walk, subjects stood quietly for the 3-minute recovery period.

**VO₂peak determination.**—Following the submaximal testing and a rest period, a symptom-limited maximum-exercise tolerance test was performed to determine VO₂peak. Due to our experience in maximal exercise testing in mobility-limited older individuals and their level of physical deconditioning, a slow-speed treadmill test was utilized, specifically, minutes 0–2 at 0.5 mph at 0% grade; minutes 3–6 at 1.0 mph at 2%, 4%, and 6% grade; minutes 7–9 at 1.5 mph at 8%, 10%, and 12% grade; minutes 10–12 at 2.0 mph at 13%, 14%, and 15% grade; minutes 13–15 at 2.8 mph at 16%, 17%, and 18% grade; and, if necessary, minutes 16–20 at 3.4 mph and at 22%, 23%, and 24% grade.

**Mobility Tasks**

A series of mobility tasks were performed on a separate day. These tasks were chosen because of the likelihood that they reflected aerobic function, i.e., endurance, rather than just balance and strength.

**Bag-carrying test.**—Subjects walked a circuit carrying 1 grocery bag in their preferred hand for 7.5 level meters, and then back 7.5 level meters. After completion of each circuit, 1.0 kg of weight was added until the subject could no longer complete the circuit carrying the bag (6). The total maximum weight ultimately carried was noted (lbs).

**Get-up-and-go test (GUG).**—Subjects rose from a standard chair, walked 3 meters, turned around, walked back 3 meters, and sat back in the chair (GUG × 1). After timing was completed for 1 circuit, this task was completed 3 times without stopping to rest, and the timing for 3 successive circuits was noted (GUG × 3).

**6-Minute walk and comfortable gait speed.**—Subjects were instructed to walk at a comfortable pace in a hallway course for 6 minutes, and were encouraged to walk as far as possible without stopping. Comfortable gait speed (m/sec) was determined over a 10-meter section after the first minute of walking. The outcome for the 6-minute walk was the distance traveled over the 6-minute period.

**Data Analysis**

The 3-minute (baseline) values for oxygen uptake during rest were defined as the average values obtained from 120 to 180 seconds during the period when the subject was standing on the elevated platform. The 6-minute (end-exercise) values for oxygen uptake during the submaximal walk on the treadmill were defined as the average values obtained from 300–360 seconds during the exercise period. The 3-minute recovery values were also determined as the average values obtained from 120–180 seconds of the recovery period. Breath-by-breath data were used to evaluate the kinetics of oxygen uptake. The time constant of oxygen-uptake kinetics at the onset of exercise, tc_deficit, was determined by fitting a monoexponential function to the oxygen-uptake response using the value at rest (3 minutes) as the baseline (8). The general form of this equation (8) can be written as:

\[ Y(t) = \Delta Y(\text{steady-state})(1 - e^{-kt}) \]

where \( Y(t) \) is the \( \text{VO}_2 \) above baseline at any time \( t \), \( \Delta Y \) is the steady state increase in \( \text{Y} \) for \( \text{VO}_2 \) and \( k \) is the rate constant of the reaction with the dimension of \( t^{-1} \). The monoexponential model with delay is appropriate to characterize the parameters of the kinetic response in older subjects (19). The time constant of the excess postexercise oxygen consumption (EPOC), tc_EPOC, was determined using the same method. This method has been found to be appropriate in modeling the oxygen-uptake kinetics following exercise in older cardiac patients (12). See Figure 1 for a sample oxygen-uptake kinetics tracing from an Unimpaired and an Impaired group subject.

Using independent t-tests, Impaired-Unimpaired group comparisons were made in VO₂peak, tc_deficit, tc_EPOC, and functional mobility test variables. Pearson’s correlation was used to correlate these same variables according to group (Impaired and Unimpaired). Self-report ADL items were scored as disabled (up to a total score of 7), Nagi items were scored as any items with at least a little difficulty (up to a total score of 5), and Rosow-Breslau items were scored as any items as unable (up to a total score of 3). Because of the limited distribution of these self-report variables, Impaired–Unimpaired group median differences were compared using nonparametric Mann-Whitney U Tests.

**RESULTS**

**Subject Description**

Subject characteristics for Unimpaired and Impaired groups appear in Table 1. The Impaired group was older than the Unimpaired group \( (p < .05) \). While few Impaired had any ADL disability, disability in terms of self-report Nagi and Rosow-Breslau items was significantly greater than in the Unimpaired \( (p < .05 \text{ for both items}) \).

**VO₂peak and Oxygen-Uptake Kinetics**

By definition, the mean VO₂peak was 58% lower in the Impaired than the Unimpaired (see Table 2). The time constant for oxygen deficit, tc_deficit, was more than twice as high in the Impaired than the Unimpaired \( (p < .05) \), and the time constant for EPOC, tc_EPOC, was 43% higher in the Impaired than the Unimpaired (borderline significance at \( p = .09) \).

**Functional Performance**

As expected, the more functionally disabled (by self-report) Impaired performed more poorly than the Unimpaired (see Table 3). As indicated by the GUG and comfortable gait velocity, the Impaired were not only slower than the Unimpaired \( (p < .05) \), but performed in ranges similar to other impaired older adult populations (20).
Compared with the Unimpaired, the Impaired were significantly slower in the serial GUG, carried lower maximum weight in the bag-carrying test, and traveled less distance on the 6-minute walk (all $p < .05$).

**Relationships Between VO$_2$peak, Oxygen-Uptake Kinetics and Functional Performance**

Table 4 shows the relationships between VO$_2$peak, oxygen-uptake kinetics, and functional performance. In the Unimpaired, VO$_2$peak is a significant predictor of both the single and serial GUG, and the 6-minute walk tests. The time constant for oxygen deficit, tc$_{deficit}$ also predicts the single and serial GUG and peak VO$_2$. The time constant for EPOC, tc$_{EPOC}$, relates only to the bag-carrying test. Thus, for the Unimpaired, tc$_{deficit}$ predicts functional performance generally as well, if not better, than VO$_2$peak. For the Impaired, the predictors differ. VO$_2$peak predicts only the 6-minute walk test, and tc$_{deficit}$ is not a strong predictor of any functional test. Oxygen-uptake kinetics following exercise, i.e., tc$_{EPOC}$, predicts not only VO$_2$peak but nearly all of the functional tests. Moreover, for the Impaired, the relationships between tc$_{EPOC}$ and the functional tests are as strong or stronger than the relationships between VO$_2$peak and the functional tests. This means that, for the Impaired, tc$_{EPOC}$ is at least as good, if not a better, predictor of function than VO$_2$peak.

**DISCUSSION**

Compared with older adults without aerobic impairment based on peak VO$_2$ measures, older adults with impairments in aerobic capacity as defined by the Social Security Administration were found to have a delay in oxygen-uptake kinetics (particularly in oxygen-deficit assessment) and poorer functional mobility both by report and performance. Measures of oxygen-uptake kinetics were as strong or more strongly predictive of functional mobility performance than peak VO$_2$peak in both Unimpaired and Impaired older adults. The major predictor of functional performance for the Unimpaired was a measure of oxygen deficit accruing during exercise (tc$_{deficit}$), and for the Impaired, it was a measure of the excess postexercise oxygen consumption during recovery, tc$_{EPOC}$.

Assessment of maximal oxygen uptake VO$_{2}$max is often limited in disabled older adults because of musculoskeletal and neuromotor impairments. Nevertheless, even when a maximal test is performed and the criteria for VO$_{2}$max is not achieved, the resulting VO$_2$peak is still correlated with both self-reported and performance-based function (2,3,6,21). The actual strength of this correlation varies, and for specific functional performance tests relevant to the present study ranges widely, e.g., 0.67 for VO$_2$peak versus bag-carrying test total weight (6) to 0.34 for VO$_{2}$max versus comfortable gait speed (21). Correlations between 6-minute walk distance and either VO$_{2}$max or VO$_2$peak range more
widely, and may show not even correlate significantly (22). In the present study, correlations between VO2peak and functional performance were modest, particularly regarding the 6-minute walk test. Thus, while it is certain that impairment in oxygen uptake affects function at some level, the relationship between the two is not simple. For example, despite our use of 18 ml/kg/min as a cutoff for the Impaired group, the existence of a threshold at which impaired VO2 affects function is not clear (3) and likely involves a complex interaction of other factors [such as leg strength (21)].

The apparent differences between the two time constants and functional performance according to impairment group may be important. In relatively able older adults (i.e., the Unimpaired), VO2peak may be a valid measure and more sensitive to the initial exercise load (i.e., the oxygen deficit). These Unimpaired older adults recover relatively quickly from the submaximal load, with minimal apparent “fatigue.” Functional performance in these older adults apparently has little to do with recovery kinetics perhaps because the postexercise oxygen consumption is relatively small in comparison to those individuals who have impairments in functional performance. On the other hand, the Impaired are stressed by the initial load as indicated by the group differences in oxygen deficit (tc_deficit) but, more importantly, they may be eventually unable to achieve a valid peak VO2peak, i.e., their peak value is attenuated. Moreover, these Impaired are undoubtedly more fatigued by the submaximal load than the Unimpaired and take longer to recover. The oxygen consumption during the recovery period, if analyzed to its actual return to rest, may be less sensitive to the initial exercise load (i.e., the oxygen deficit).

Functional performance in these older adults appears to have a threshold at which impaired VO2 affects function and thus may be a more practical measure of aerobic function. The submaximal oxygen-uptake kinetics measures provide a more relevant assessment of deconditioning in frail older adults, and may eventually supplant maximal (peak) oxygen uptake as a predictor of functional disability in older adults.

Measurement of oxygen-uptake kinetics during a submaximal test does not require the effort of a maximal test, and thus may be a more practical measure of aerobic function. The submaximal oxygen-uptake kinetics measures may provide a more relevant assessment of deconditioning in frail older adults, and may eventually supplant maximal (peak) oxygen uptake as a predictor of functional disability in older adults.

Measures of aerobic function such as oxygen-uptake kinetics may also be important additions to models of frailty in older adults. A recently published sarcopenia-based model of frailty (23) uses muscle weakness (grip strength), self-reported exhaustion, and low activity levels as frailty indicators. These frailty indicators also suggest a deconditioned state, and are particularly common in individuals with overt or subclinical cardiovascular disease burden (24). A link between cardiovascular dysfunction, sarcopenia, and frailty seems logical (25), and an important way to probe this link could be measures of aerobic function that directly relate to disability. Submaximal oxygen-uptake kinetics could be used as such a measure. Furthermore, aerobic exercise-induced improvements in aerobic function in patients with cardiac disease involve peripheral muscle adaptations (26). Thus, interventions to reduce frailty by reducing sarcopenia might well consider interventions beyond resistance training.

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### Table 3. Mean (± SEM) Functional Performance in Impaired and Unimpaired Groups

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Unimpaired</th>
<th>Impaired</th>
</tr>
</thead>
<tbody>
<tr>
<td>GUG (s)</td>
<td>12 (1)</td>
<td>20 (2)*</td>
</tr>
<tr>
<td>Serial GUG (GUG ( \times 3 ), s)</td>
<td>33 (2)</td>
<td>54 (5)*</td>
</tr>
<tr>
<td>Bag-carrying test (maximum weight, lb)</td>
<td>14 (1)</td>
<td>8 (1)*</td>
</tr>
<tr>
<td>6-Minute walk (total distance, m)</td>
<td>415 (17)</td>
<td>286 (27)*</td>
</tr>
<tr>
<td>Comfortable gait velocity (m/s)</td>
<td>1.2 (0.1)</td>
<td>0.8 (0.1)*</td>
</tr>
</tbody>
</table>

*Notes: *p < .001. GUG = get-up-and-go test.

### Table 4. Relationships Between VO2, Oxygen Uptake Kinetics, and Functional Performance in Unimpaired and Impaired Older Adults

<table>
<thead>
<tr>
<th>Task</th>
<th>Peak VO2</th>
<th>tc_deficit</th>
<th>tc_EPOC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unimpaired Old</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak VO2</td>
<td>0.62**</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>GUG</td>
<td>0.48*</td>
<td>0.58*</td>
<td>0.06</td>
</tr>
<tr>
<td>GUG ( \times 3 )</td>
<td>0.55*</td>
<td>0.60**</td>
<td>0.13</td>
</tr>
<tr>
<td>Bag carry</td>
<td>0.29</td>
<td>0.22</td>
<td>0.59**</td>
</tr>
<tr>
<td>6-Minute walk</td>
<td>0.45*</td>
<td>0.31</td>
<td>0.15</td>
</tr>
<tr>
<td><strong>Impaired Old</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak VO2</td>
<td>0.11</td>
<td>0.49*</td>
<td></td>
</tr>
<tr>
<td>GUG</td>
<td>0.21</td>
<td>0.10</td>
<td>0.42</td>
</tr>
<tr>
<td>GUG ( \times 3 )</td>
<td>0.41</td>
<td>0.02</td>
<td>0.33</td>
</tr>
<tr>
<td>Bag carry</td>
<td>0.35</td>
<td>0.07</td>
<td>0.53*</td>
</tr>
<tr>
<td>6-Minute walk</td>
<td>0.62**</td>
<td>0.18</td>
<td>0.64**</td>
</tr>
</tbody>
</table>

*Notes: *p < .01, *p < .05. VO2 = oxygen uptake; GUG = get-up-and-go test; tc = time constant; EPOC = excess postexercise oxygen consumption.
REFERENCES


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