Torque-velocity relation of pedaling movement against stepwise increase in load

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[Received December 10, 2004 ; Accepted February 8, 2005]

Using a recumbent-type cycle ergometer, we investigated the validity of using a stepwise increment in load within a bout of exercise to determine the torque-velocity relation of pedaling movement. Fourteen healthy men and women performed pedaling exercise at their maximal effort on a recumbent-type cycle ergometer with an electromagnetic load control. Two types of loading were used: a conventional method (C) in which a varied load was applied to each bout independently; a "stepwise loading" method (S) in which the load was successively increased within a bout. In S, the external load was not applied initially, but when axial rotation velocity reached a maximum, it was increased in a stepwise manner until the velocity declined to 30% of the maximum. The torque-velocity relations obtained by both methods (C and S) were well described with linear functions and substantially identical, indicating that the present stepwise loading method is useful for a rapid evaluation of lower-limb muscle function.

Keywords: force-velocity relation, multi-joint movement, recumbent cycle ergometer

1. Introduction

To evaluate human motor activity, it is important to quantify physiological and mechanical properties of muscle in vivo using such parameters as strength, speed and power. During the decades, various methods have been proposed for this purpose, i.e., the jumping test (Sargent, 1921), the stair sprinting test (Margaria et al., 1966), and the sprint cycling test such as Wingate test (Bar-Or, 1987). These methods aim to evaluate the maximal, explosive power output from either single bout of exercise or maximum exercise lasting for ~10s.

The mechanical performance of lower-limb muscle has often been measured with the cycle ergometer in both field and laboratory tests. Since mechanical power is the product of force and velocity, maximum power can be appropriately determined only when its peak value is found according to the force-velocity relation. Some studies on the torque-velocity relation of pedaling exercise have shown that the velocity is a function of force and the maximum power is developed at particular force (Driss et al., 1998, 2002; Shibukawa et al., 1968; Vandewalle et al., 1987). However, determining the force-velocity relation requires repeated measurements with varied load and is therefore time-consuming. In addition, the torque-velocity relation of the recumbent-type pedaling exercise has not so far been reported. The test using recumbent-type pedaling exercise is expected to be useful in rehabilitation and training for elderly people because a recumbent position bears lower risk for low back pain as compared with the sitting position (Boissonnault and Fabio, 1996). Thus, the present study investigated the torque-velocity relation of a recumbent-type pedaling exercise and the validity of using a stepwise increment in load within a bout of exercise to determine the torque-velocity relation rapidly.
2. Methods

2.1. Subjects

Fourteen healthy men and women (age, 23.43±5.36 yr; height, 162.41±8.15 cm; body mass, 54.35±6.64 kg, mean±S.D.) participated in the study. The methods and all procedures were in accordance with current local guidelines and the Declaration of Helsinki, and were approved by the Ethical Committee for Human Experiments, The University of Tokyo. All of the subjects were previously informed well about the experimental procedure as well as the purpose of the study, and gave their written informed consent.

2.2. Experiment procedure

Subjects performed pedaling exercise at their maximal effort on a recumbent-type ergometer with an electromagnetic load control (Matsushita Electric Works Ltd.). Figure 1 illustrates the whole system. The braking force command was generated by a personal computer and transmitted to an electromagnetic brake. Torque and pedaling revolution rate were measured with a torque meter and a photo-coupled switch placed at the edge of pulley, respectively. The recline angle of the seat was fixed at 55 degrees, based on previous EMG measurements showing the most balanced activation of knee and hip extensor muscles without large stress on back muscle during the knee-hip extension movement (data not shown). Horizontal distance between the seat and the center of crank was adjusted to fit the physical dimension of each subject. Subjects were secured on pelvis and trunk with straps and on shoulders with fixable pads, and instructed to pedal without raising their hip from the seat. Before each experiment, subjects made warm-up for a few minutes at their own cycling pace and stretching of the quadriceps, the hamstrings and the triceps surae muscles. Then, they practiced two bouts of exercise at a maximum speed for 3-5s. Prior to the experimental session, some additional practice sessions were made to familiarize them with the testing apparatus and procedure.

In the experimental session, pedaling exercise was performed at their maximal effort. Measurements were randomly made with two types of loading methods: a conventional method (C) in which a varied load was applied to each bout independently, and a "stepwise loading" method (S) in which the load was successively increased within a bout. In C, subjects performed maximum sprints against different braking forces. They started to pedal without the external load for 30s, and then accelerated the pedaling to a maximum speed against the preset braking force and kept the exercise until torque and velocity reached a constant level. In S, following a 30s pedaling without load, they tried to accelerate the pedaling to a maximum speed in 3-6s. When the axial rotation
velocity of the pedal reached a maximum, the braking force started to increase in a stepwise fashion for every 2 revolutions. They continued to perform pedaling at their maximum effort until the velocity declined to 30% of the maximum speed. The duration of applying the braking force depended on subjects and ranged between 5s and 12s.

The subjects performed 2 trials for each method and were allowed to rest for 5-10 min between each trial. Verbal encouragement was given throughout each test. Torque (Nm), velocity (pedaling revolution rate: rpm) and braking force command were continuously monitored. To determine the torque-velocity relation, maximum values of torque as the velocity reached a steady level were measured in C. In S, torque and velocity at maximum torque production in the 2nd cycle of pedaling were measured because those in the 1st cycle might be affected by an increasing phase of braking force (Figure 2). Our preliminary measurements have shown that the

Figure 2  Typical examples of torque and velocity measurements. A, conventional method. B, "stepwise loading" method. In A, a constant braking force (50Nm) was applied throughout. In B, a braking force (initially 40Nm) was increased in a stepwise fashion (step, 5Nm) after an acceleration phase without braking force. The portions of torque records (a) and (b) in A and B, respectively, are shown at enlarged time scales (panels on the bottom). Arrows indicate points of measurement.
maximum pedaling torque was similar between left and right legs in untrained subjects, so that the torque was obtained from only one side of the leg (left). The reproducibility of the measurement was assessed with a test-retest procedure, and 7 out of all subjects were chosen for a retest separated by 2 weeks.

2.3. Data analysis

Data are presented as mean ± S.D. Differences between methods were examined with paired t-test. Least squares regression analysis was made for the relations between torque and velocity. Statistically significant level was set at P<0.05.

3. Results

The torque-velocity relations of pedaling exercise determined with both C and S methods were well described with linear functions as shown in Figure 3. Correlation coefficients between torque and velocity were r=-0.939 to -0.993 and r=-0.905 to -0.998 for C and S, respectively. Therefore, the maximum isometric torque (Tmax) and the unloaded pedaling revolution rate (Rmax) were estimated with extrapolating the linear regressions onto the torque and velocity axes, respectively, in both C and S methods. Tmax and Rmax determined by S method did not show significant differences (P>0.05) from those obtained from C method: Tmax = 121.57±31.05Nm (S) vs. 125.92±28.74Nm (C); Rmax = 201.61±28.13rpm (S) vs. 195.65±23.48rpm (C). Correlation coefficients between S and C were r=0.91 (P<0.01) and r=0.80 (P<0.01) for Tmax and Rmax, respectively. In addition, no differences were seen between S and C methods when the velocities at...
representative torques (30, 50 and 70% of \( T_{\text{max}} \) determined by C method) were estimated from the regression lines and compared (Table 1).

The reproducibility of the torque-velocity test with S method was examined by means of repeated measurements separated by 2 weeks. Values of \( T_{\text{max}} \) and \( R_{\text{max}} \) for 2\(^{\text{nd}}\) measurement were well correlated with those for 1\(^{\text{st}}\) measurement (\( r=0.84 \) and \( r=0.95 \) for \( T_{\text{max}} \) and \( R_{\text{max}} \), respectively; \( n=7 \)).

4. Discussion

The present linear-like nature of torque-velocity relation of the recumbent-type pedaling exercise is in agreement with that of regular, upright pedaling exercise reported elsewhere (Driss et al., 1998, 2002; Vandewalle et al., 1987). Also, we have recently shown the linear appearance of steady-state force-velocity relation in human knee-hip extension movement determined with a servo-controlled dynamometer (Yamauchi et al., 2004). The force-velocity relations of the multi-joint movements represented by knee-hip extension may have a linear nature rather than hyperbolic one shown in an isolated muscle (Hill, 1938) and a single joint movement (Wilkie, 1950). However, the mechanisms underlying this linear appearance of force-velocity relation remain unclear. The hyperbolic nature of force-velocity relation can be seen in the interaction between single thick filaments and actin, so that it can be regarded as ubiquitous in muscle contraction (Ishii et al., 1997). Therefore, it can be speculated that the changes in the activation level among working muscles affect the form of force-velocity relation in human multi-joint movements. It has been shown that the ability to generate power during voluntary pedaling exercise is affected by either external load or pitch (Shibukawa et al., 1968) and that patterns of electromyographic activities of working muscles change with crank angular velocity (Neptune and Herzog, 2000). In addition, coordination between agonist and antagonist muscles may also be important.

Evaluation of muscular function in aged population is important, because it provides the basis for an adequate exercise prescription to overcome the aging-related decline in muscular strength. In particular, keeping or improving lower limb muscle function is important because it is not only affected strongly by aging, but also closely related to the daily activity for living. For these reasons, the measurement of maximum isometric strength has been widely used for evaluating lower limb muscular functions (Abernethy et al., 1995). However, it has been reported that maximum isometric strength test induces some symptoms of orthopedic injuries in ~20% of individuals older than 70 years because of large mechanical stress around joints (Pollock et al., 1991). Although the dynamic method may reduce such a possibility, measurement of one repetition maximum (1RM), for example, may not completely exclude the risk for injury (Shaw et al., 1995). Also, isokinetic measurements may be associated with some difficulties in attaining maximum activation of muscles within a short range of motion (Perrine and Edgerton, 1978).

Since the torque-velocity relation of the recumbent-type pedaling exercise exhibited a linear function, both the maximum isometric torque (\( T_{\text{max}} \)) and the velocity at zero torque (\( R_{\text{max}} \)) were successfully estimated by an extrapolation. The lower correlation between 1\(^{\text{st}}\) and 2\(^{\text{nd}}\) measurements

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Table 1  Values of velocity (Mean±S.D.) at representative relative torques.  To compare S and C methods, the velocities at the same relative torques (relative to \( T_{\text{max}} \) determined by C method) were shown for both S and C methods.  No significant difference was seen between the methods.

<table>
<thead>
<tr>
<th>Torque (%( T_{\text{max}} ))</th>
<th>Velocity (rpm) S method</th>
<th>Velocity (rpm) C method</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>139.72±22.39</td>
<td>136.95±16.44</td>
</tr>
<tr>
<td>50</td>
<td>98.52±18.33</td>
<td>97.82±11.74</td>
</tr>
<tr>
<td>70</td>
<td>57.33±16.35</td>
<td>58.69±7.05</td>
</tr>
</tbody>
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for $T_{max}$ than that for $R_{max}$ was due possibly to day-to-day variations in strength (Driss et al., 2002). It has been shown that the maximum isometric force extrapolated from the force-velocity relation of usual pedaling in upright position is correlated with various strength-related parameters for knee extension determined with isometric and isokinetic measurements (Driss et al., 2002). On the other hand, $R_{max}$ may reflect both neuromotor control for high-velocity movement and muscle fiber composition (Thorstensson et al., 1976; Tihanyi et al., 1982), both of which are important factors when changes in neuro-muscular function after exercise and aging are considered.

In conclusion, the torque-velocity relation of recumbent-type pedaling exercise was successfully determined by using a stepwise loading protocol within a bout of exercise, and showed a linear appearance. The present method can be useful for a rapid evaluation of lower limb strength, speed and power with relatively small physical stress.

**References**


