Force–Velocity and Power–Velocity Relationships during Maximal Short-Term Rowing Ergometry

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ABSTRACT

SPRAGUE, R. C., J. C. MARTIN, C. J. DAVIDSON, and R. P. FARRAR. Force–Velocity and Power–Velocity Relationships during Maximal Short-Term Rowing Ergometry. *Med. Sci. Sports Exerc.*, Vol. 39, No. 2, pp. 358–364, 2007. **Introduction:** Maximal rowing power–velocity relationships that exhibit ascending and descending limbs and a local maximum have not been reported. Further, duty cycle (portion of the stroke occupied by the pull phase) is unconstrained during rowing and is known to influence average muscular power output. **Purpose:** Our purposes for conducting this study were to fully describe maximal short-term rowing force–velocity and power–velocity relationships. Within the context of those purposes, we also aimed to determine the apex of the power–velocity relationship and the influence of freely chosen duty cycle on stroke power. **Methods:** Collegiate varsity male rowers ($N = 11$, 22.9 ± 2.3 yr, 84.1 + 12.1 kg, 184 ± 7 cm) performed five maximal rowing trials using an inertial load ergometer. For each stroke, we determined force and power averaged for the pull phase and the complete stroke, instantaneous peak force and power, average handle velocity for the pull phase, handle velocity at peak instantaneous force and power, pull time, recovery time, and freely chosen duty cycle. Force–velocity and power–velocity relationships were characterized using regression analyses, and optimal velocities were determined from the regression coefficients. **Results:** Pull force–velocity ($r^2 = 0.99$) and peak instantaneous force–velocity ($r^2 = 0.93$) relationships were linear. Stroke power ($r^2 = 0.98$), pull power ($r^2 = 0.99$), and instantaneous peak power ($r^2 = 0.99$) were quadratic, with apexes at 2.04, 3.25, and 3.43 $m{\cdot}s^{-1}$, respectively. Maximum power values were 812 ± 28 W (9.8 ± 0.4 $W{\cdot}kg^{-1}$), 1995 ± 67 W (23.9 ± 0.7 $W{\cdot}kg^{-1}$), and 3481 ± 112 W (41.9 ± 1.3 $W{\cdot}kg^{-1}$) for stroke, pull, and instantaneous power, respectively. Freely chosen duty cycle decreased from 58 ± 1% on the first stroke to 26 ± 1% on the fifth stroke. **Conclusions:** These data characterized the maximal rowing force–velocity and power–velocity relationships and identified the optimal velocity for producing maximal rowing power. Differences in maximum pull and stroke power emphasized the importance of duty cycle. **Key Words:** MUSCLE, NEUROMUSCULAR, ANAEROBIC, ERGOMETER

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Maximal force–velocity and power–velocity relationships have been reported for several human activities including cycling and rowing (7,12,15,19,20,22), both of which are cyclic leg extension activities. Several authors have reported that maximal cycling torque (or pedal force) decreases linearly with velocity (15) and, therefore, contrasts with the hyperbolic Hill-type force–velocity relationship (8) that is characteristic of fully excited isolated muscle, as well as elbow flexion (23) and knee extension (21). That contrast is likely attributable, in part, to excitation/relaxation kinetics, which reduce muscle activation during cyclic contractions (2,11,17). Interestingly, Hartmann and colleagues (7) have reported that the rowing force–velocity relationship was well represented by a Hill-type curve. Such a relationship might be reasonable for rowing because the leg extensors are likely used in a braking action at the end of the recovery phase and, thus, might be less influenced by excitation/relaxation kinetics (11). However, the data Hartmann et al. (7) present to support that Hill-type relationship can be interpreted to suggest that the relationship might be even better approximated by a linear function (see Figure 7 in Hartmann et al. (7)).

Cycling power–velocity relationships have been reported to be quadratic and exhibit a well-defined apex at approximately 120–130 rpm (12,15,19,20,22). To our knowledge, only Hartmann and colleagues (7) have reported short-term, maximal, rowing power–velocity relationships. They reported a curvilinear increase in instantaneous peak power during five-stroke maximal trials, suggesting that all five strokes were performed on the ascending limb of the power–velocity relationship. Mandic and colleagues (10) have reported the rowing power–resistance relationship for a modified Wingate

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anaerobic test. Their data indicate a monotonic increase in peak 5-s power with increasing resistance for the lightweight male rowers, suggesting that all the resistances evaluated were less than optimal and, therefore, represented the descending limb of the power–velocity relationship. Thus, the apex of the rowing power–velocity relationship has yet to be clearly established.

Although rowing and cycling are similar in that they require cyclic leg extension, they differ with regard to unilateral versus bilateral activity and relative time spent in leg extension. During cycling, leg extension occupies 50% of the time for a cycle (50% duty cycle), and the legs produce an alternating series of unilateral power pulses with minimal lag between pulses. In contrast, rowers produce bilateral leg extension power pulses followed by recovery periods in which no propulsive power is delivered to the handle. Further, the ratio of time for the pull and the complete stroke (pull time plus recovery time) are not coupled, allowing rowers to manipulate duty cycle, which is known to alter muscular power during unilateral cycling and isolated muscle work loops (1,13).

To examine the maximal rowing force–velocity and power–velocity relationships, we adapted the inertial load method we previously established for cycling (15) and used this adapted method in the current study. Our main purposes for conducting this study were to fully describe the maximal short-term rowing force–velocity and power–velocity relationships. Within the context of those main purposes, we also aimed to determine the apex of the power–velocity relationship and the influence of freely chosen duty cycle on stroke power.

METHODS

Eleven well-trained male collegiate varsity rowers (22.9 ± 2.3 yr, 84.1 + 12.1 kg, 184 ± 7 cm) volunteered to participate in this investigation. We explained the testing procedures to the volunteers, each of whom provided written informed consent before participating. The institutional review board at the University of Texas at Austin reviewed and approved procedures used in this study.

Participants reported to the laboratory at least 12 h postprandial and performed a 3-min warm-up on a conventional rowing ergometer (Concept II Model C, Morrisville, VT) at a modest effort of 100–150 W. After a 2-min rest, participants moved to a modified ergometer (Concept II Model C, Morrisville, VT; modifications detailed below) and performed five maximum-intensity trials, each consisting of six pulls. Rowers started from a standardized position with the handle placed in the handle hook and initiated the pull phase of the first stroke on a verbal command. The duration of the six-stroke trials, from the start of the first pull to the end of the pull portion of the sixth stroke, was approximately 7 s, with approximately 3 s occupied by the six pull phases. Rowers performed 2 min of self-paced unloaded rowing between trials. To help stabilize the rowers during these maximal efforts, we added a high-friction seat cover, a seat belt, and a plastic rear lip to the seat, and we bolted the ergometer to a concrete floor.

To fully describe the rowing power–velocity relationship, we modified a Concept 2 Model C rowing ergometer to measure power delivered to the flywheel using the inertial load method, which we previously developed for measuring cycling torque–velocity and power–velocity relationships (15). In this method, force is required to overcome inertia as the rower maximally accelerates the flywheel from rest for a specified number of strokes. We modified the flywheel by removing the fan vanes and adding brass masses to increase the moment of inertia (see moment of inertia calculation below for full description). Flywheel moment of inertia is of key importance for this technique because it must be small enough to allow subjects to reach velocities greater than the apex of the power–velocity relationship in a short time to avoid fatigue. Conversely, it must be large enough that subjects will not reach or exceed the velocity for maximum power in the first pull. During pilot testing, we evaluated a fivefold range of flywheel moment of inertia values from 0.07 to 0.35 $kg \cdot m^{-2}$. Those pilot data indicated that a moment of inertia of 0.095 $kg \cdot m^{-2}$ allowed trained rowers to reach maximum pull power by the third or fourth stroke, thereby assuring that rowers would reach and exceed the apex of the power–velocity relationship in a six-stroke trial. In our original cycling paper (15), we noted that inertial loads over a large range enabled subjects to produce similar maximum power values. Thus, we believe that a single inertial load, chosen as described above, was appropriate for this study. We calculated the moment of inertia of the flywheel (I) as the sum of the component parts. The flywheel was treated as a disk (I = 1/2 (mr^2), where m is the flywheel mass and r is the outside radius of the flywheel); fasteners (nuts, bolts, and washers) were treated as point masses on the disk ($I = mr^2$, where m is the mass of each fastener and r is the distance from the axis of rotation to the fastener); the brass masses were treated as rotating bodies using the parallel axis theorem ($I = I_{com} + mr_w^2$, where I_{com} is the moment of inertia of each mass about its own center of mass, m is the mass, and r_w is the radial distance from the axis of rotation of the flywheel to the center of the brass masses); and the components of the hub were treated as cylindrical shells ($I = mr^2$, where m is the mass of each component and r is its radius).

The time–position trajectory of the flywheel was determined as previously described (15). Briefly, a slotted disc was mounted on one side of the flywheel and an infrared photodiode and detector were mounted on the ergometer frame. Fourteen slots were separated by an angular displacement of $\pi/8$ radians ($\Delta\Theta$), and one index slot was separated by an angular displacement of $\pi/4$ radians along the perimeter of the disk. The index slot allowed identification and measurement of the angle between each individual slot to correct for machining tolerances in the slots. The surface of the disk reflected the infrared beam, and slots failed to reflect (interrupted) the infrared beam. The detector circuit was programmed to emit a square pulse at each interrupt. The time between

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consecutive interrupts was recorded by a dedicated microprocessor with a clock accuracy of $\pm 0.5 \mu s$.

Position–time data were filtered using a quintic generalized cross-validation spline procedure (24) with a cutoff frequency of 8 Hz. Flywheel angular velocity (ω) and angular acceleration (α) were calculated from the spline coefficients. Instantaneous handle velocity was calculated as $v = \omega r_{as}$, where r_{as} = the radius of the axle sprocket (0.014 m). In our previous use of the inertial load method for cycling, we only evaluated the torque and power required to accelerate the flywheel (which had a smooth surface). In the present application, even though we removed the fan vanes from the rowing ergometer flywheel, we observed that the added masses caused a substantial aerodynamic drag. Therefore, we determined the aerodynamic drag and bearing friction by collecting time–position data while the flywheel decelerated from maximal speed. We then calculated torque for each point and fitted the torque–angular velocity data to a polynomial function where the second-order term represents aerodynamic drag and the intercept represents friction losses (14). We also accounted for force required to accelerate the handle and the chain ($f = ma$, where m is the mass of the handle or the chain and a is the acceleration), and the tension in the chain return spring ($f = k\Delta x$, where k is the spring constant and Δx is the displacement from resting length). Total force delivered to the handle was, therefore, calculated as the sum of forces to accelerate the flywheel (flywheel moment of inertia × angular acceleration/radius of the drive sprocket), force to accelerate the chain and handle (mass × acceleration), force to stretch the return spring (spring constant × displacement), and aerodynamic drag and bearing friction (determined from regression analysis of the deceleration data: torque = $0.0519 + 1.1 \times 10^{-5}\omega^2$). For each data point, power was calculated from the instantaneous force and velocity data.

Fluctuations in flywheel power allowed us to identify beginning and end points of each pull. Specifically, power was positive during the pull phase of each stroke and zero during the recovery phases. Small fluctuations in the calculated power prevented us from simply identifying the pull phase, as when power was greater than zero. Instead, we identified the point at which power fell below (at the end of the pull) or rose above (at the beginning of the pull) a threshold value (75 W). We then used linear extrapolation of five power–time points below the threshold to determine the time at which power would reach zero. These extrapolated time points were then used to calculate time for the pull and recovery phases and to determine which power and force values were averaged. Instantaneous force and power data from the pull phase of each stroke were averaged to determine pull force and pull power. Power data from the pull phase were also averaged over the time for a complete cycle (including the recovery phase after each pull) and were termed stroke power. Handle velocity was averaged over the pull phases to determine the pull force–velocity, pull power–velocity, and stroke power–velocity relationships. The highest values for instantaneous force and power within each stroke were defined as peak instantaneous forces and powers. The handle velocities at which peak instantaneous forces and powers occurred were identified and used to determine the peak instantaneous force–velocity and power–velocity relationships.

Force–velocity data were fitted to a linear function (force = $F_0 + CV$, where F_0 is isometric force, C is the slope of the force–velocity relationship, and V is handle velocity) and to a Hill-type force–velocity equation (force = $(b(F_0 + a)/(V + b)) - a$, where F_0 is isometric force, a and b are coefficients, and V is handle velocity). Power–velocity relationships for pull power, stroke power, and peak instantaneous power were determined with regression of power with handle velocity and handle velocity squared. The stroke power–stroke rate relationship was determined similarly. Optimal handle velocity and stroke rate were determined by using the regression coefficients for each power–velocity equation to identify the apex of each curve. To control for between-subject variability while retaining trial-to-trial variability when determining these relationships, data for all subjects were averaged for each of the five trials. That averaging process produced five sets (one for each trial) of force–velocity and power–velocity data for each calculated term. Finally, duty cycle, pull time, and recovery time for each stroke were analyzed with repeated-measures ANOVA. A Bonferroni alpha adjustment (0.05/3) was applied to reduce the probability of type I error and, therefore, a P value of 0.017 was used as our criterion for significance. If the ANOVA indicated significant main effects, a Tukey *post hoc* procedure was used to determine which measures differed. (Note that subjects stopped the trial at the conclusion of the sixth pull, so stroke power, duty cycle, and return time were not calculated for that final stroke.)

RESULTS

Pull force–velocity and peak instantaneous force–velocity data are presented in Figure 1. The coefficients of determination (r^2) for the linear and Hill-type approximations to the force–velocity data were nearly identical: 0.993 (linear; F_0 = 1214 N, C = −197 N·m·s^{-1}) versus 0.993 (Hill type; F_0 = 1524 N, a = 381, b = 3.21) for pull force, and 0.934 (linear; F_0 = 1557 N, C = −184 N·m·s^{-1}) and 0.933 (Hill type; F_0 = 1704 N, a = 426, b = 5.95) for instantaneous peak force. The instantaneous force–velocity data from the first pull seemed to deviate from linearity. Consequently, we performed an additional linear regression analysis without data from the first pull and found that the remaining data were much better approximated by a linear function (r^2 = 0.98, F_0 = 1808 N, C = −254 N·m·s^{-1}). Power data for each participant are presented in Table 1, where maximum stroke power, maximum pull power, and maximum instantaneous power represent the greatest values achieved during any of the five trials. A representative power trace for one trial is shown in Figure 2. Maximum stroke power was 812 ± 28 W

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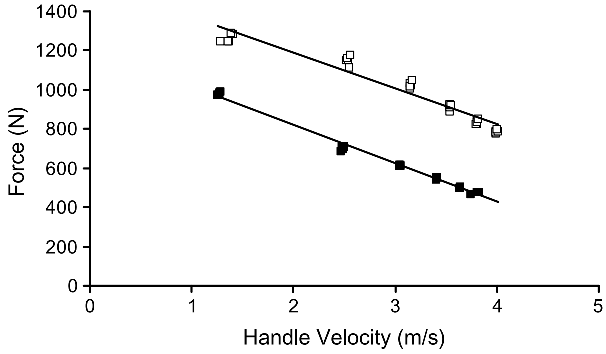

FIGURE 1—Force–velocity relationships. Pull force–velocity (■, r^2 = 0.99) and instantaneous peak force–velocity relationships (□, r^2 = 0.93) were well described by linear relationships.

(9.8 ± 0.4 W·kg^{-1}), maximum pull power was 1995 ± 67 W (23.9 ± 0.7 W·kg^{-1}), and maximum instantaneous power was 3489 ± 112 W (41.9 ± 1.3 W·kg^{-1}). The within-subjects coefficient of variation among the five trials was 3.6 ± 0.4% for maximum pull power, 4.0 ± 0.5% for maximum stroke power, and 3.8 ± 0.6% for maximum instantaneous power. Stroke power–velocity (r^2 = 0.978; power = $-89V^2 + 364V + 413$), pull power–velocity (r^2 = 0.986; power = $-158V^2 + 1025V + 189$), and instantaneous peak power–velocity relationships (r^2 = 0.99; power = $-415V^2 + 2852V - 1639$) were well described by quadratic relationships (Fig. 3). Optimal handle velocity, predicted from the regression equations, was 2.04 m·s^{-1} for stroke power, 3.25 m·s^{-1} for pull power, and 3.43 m·s^{-1} for instantaneous power. The stroke power–stroke rate relationship (Fig. 4) was less well defined by our present protocol (r^2 = 0.38; power = -2.39 rate^2 + 191 rate $-$ 3021) with an optimal stroke rate of 40 strokes per minute. Duty cycle decreased significantly with each successive stroke, from 58% for the first stroke to 26% for the fifth stroke (P < 0.001). That decrease was attributable to decreased pull time, which decreased with successive stroke (P < 0.001) and increased recovery time (P < 0.001) for each successive stroke (Fig. 5). Pull time decreased from 0.98 ± 0.02 s for the first pull to 0.31 ± 0.01 s for the sixth pull. Recovery time increased from 0.73 ± 0.03 s during the first stroke to 0.95 ± 0.03 s during the fifth stroke.

TABLE 1. Maximum power produced by each rower.

Rower	Maximum Stroke Power		Maximum Pull Power		Maximum Instantaneous Power	
	W	W·kg^{-1}	W	W·kg^{-1}	W	W·kg^{-1}
A	725	10.6	1767	25.7	3242	47.2
B	753	9.8	2036	26.6	3747	48.9
C	861	10.9	2129	27.1	3635	46.2
D	814	10.9	1843	24.8	3264	43.9
E	824	8.5	2365	24.4	3837	39.5
F	705	7.0	1967	19.4	3480	34.4
G	856	10.1	1921	22.7	3192	37.6
H	648	9.5	1621	23.7	2835	41.4
I	937	9.3	2173	21.5	4047	40.1
J	928	10.1	2262	24.7	3885	42.4
K	876	10.6	1858	22.6	3215	39.1
Mean	812	9.8	1995	23.9	3489	41.9
SEE	28	0.4	67	0.7	112	1.3

Maximum stroke power, maximum pull power, and maximum instantaneous power represent the greatest values achieved during any of the five trials and are presented as absolute power (W) and normalized to body mass (W·kg^{-1}).

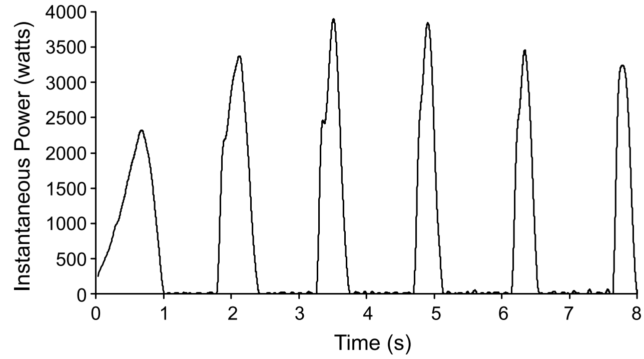

FIGURE 2—Instantaneous power data from a representative trial.

DISCUSSION

In this study we characterized maximal rowing force–velocity and power–velocity relationships and reported several aspects of maximal rowing power, including maximum values for pull power, stroke power, and instantaneous power and the apexes of the power–velocity relationships. The force–velocity relationships produced by these trained rowers were closely approximated by linear and Hill-type functions, and the power–velocity relationships were closely approximated by quadratic functions. These power–velocity data extend on and connect the ascending limb of the power–velocity relationship reported by Hartmann and colleagues (7) and the ascending limb of the power–resistance data reported by Mandic and colleagues (10). Those power–velocity relationships indicated that the handle speed for maximum instantaneous power was 3.43 m·s^{-1}, which agrees well with the velocity at which Hartmann et al.'s male subjects reached their greatest power (3.5 m·s^{-1}). Maximum instantaneous power produced by rowers who participated in this study (3489 ± 112 W) was similar to that reported by Hartmann and colleagues for male German National Team rowers

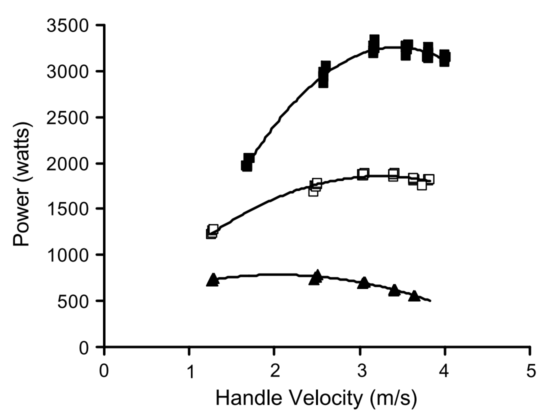

FIGURE 3—Rowing power vs handle velocity relationships. Power vs handle velocity relationships were well described by quadratic equations for stroke power (△, r^2 = 0.98), pull power (□, r^2 = 0.99), and peak instantaneous power (■, r^2 = 0.99). Apexes of those relationships occurred at 2.04, 3.25, and 3.43 m·s^{-1} for stroke power, pull power, and instantaneous peak power, respectively.

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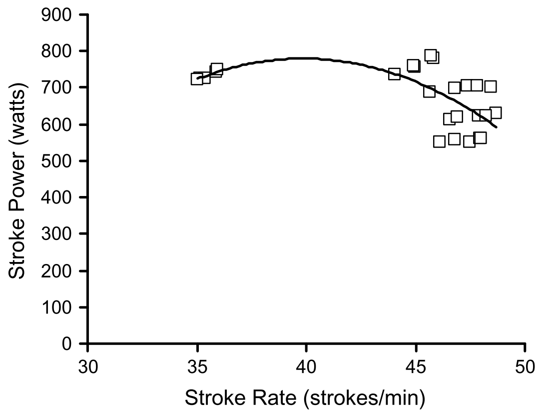

FIGURE 4—Stroke power vs stroke rate. Stroke power vs stroke rate relationship was described by a quadratic relationship (r^2 = 0.38).

(3230 ± 353 W). Further, maximum stroke power produced by our rowers (812 ± 28 W) was quite similar to the 5-s peak power values reported by Mandic and colleagues for heavy-weight rowers (807 ± 122 W). Thus, several aspects of our data, obtained with a modified inertial load rowing ergometer, agree well with previously reported data.

The observation that our force–velocity data were equally well approximated by linear and hyperbolic equations surprised and intrigued us. We believe that this similarity is attributable more to the flexibility of the hyperbolic equation than to the curvature of the data. Indeed, to test this notion, we generated a set of truly linear data and were able to approximate it with a hyperbolic equation with an r^2 value of > 0.9999. Thus, we conclude that our pull force–velocity relationships were essentially linear and, therefore, similar to relationships reported for cycling. This was an area of interest for us because the linear cycling force–velocity relationships are influenced by excitation/relaxation kinetics (11,17). During rowing, however, leg extensors must be activated to stop the recovery phase (i.e., a braking action). Consequently, we believe that the leg extensor muscles might be less influenced by excitation/relaxation kinetics and that the rowing force–velocity relationship would more closely resemble the relationship for fully activated muscle. Because this was not the case, the underlying mechanism for the linear force–velocity relationships for cycling and rowing remain unknown. We speculate that the mechanism(s) likely involve the multimuscle (including uniarticular and biarticular), multijoint nature of these two activities. Finally, although the force–velocity data were generally quite linear, the instantaneous force produced during the first pull deviated (was lower) from linear. That deviation may be related to the fact that our subjects performed the first pull from rest and that the leg extensor muscles were likely not subject to stretch-enhanced force production, as they were in subsequent pulls (5). In future investigations, we plan to instruct subjects to begin each trial with a recovery phase to eliminate this issue.

The stroke power–stroke rate relationships produced by our subjects indicate that maximum stroke power should occur at a stroke rate of 40 strokes per minute, which is within the range of stroke rates selected during Olympic rowing competition: 36–41 strokes per minute for men (9). Further, stroke power was influenced by power produced during the pull phase and by the time required for the rower to return to a position to start the next pull: a freely chosen duty cycle. Because of those two factors, maximum stroke power occurred at a lower handle velocity (2.04 $m \cdot s^{-1}$) than maximum pull power (3.25 $m \cdot s^{-1}$). Data from the first and fifth strokes in our trials illustrate the influence of duty cycle. For the first stroke, our subjects averaged 1243 W for the pull and 733 W for the stroke because of the 58% duty cycle. During the fifth stroke, our subjects produced 1819 W for the pull but only 556 W for the stroke because of the 26% duty cycle. Thus, although pull power increased by 46%, stroke power decreased by 24%, concomitant with the decrease in duty cycle. These data emphasize the importance of duty cycle in rowing, which is known to influence maximal power produced during work loops performed by isolated muscle (1) and produced by humans performing maximal single-leg cycling (13). It may be important to note that we instructed our subjects to perform six rowing strokes with maximal power but that we gave no instruction regarding the return phase. Thus, they freely adopted the duty cycles we observed. In future studies, we may manipulate duty cycle in a systematic way to determine whether rowers are capable of maintaining pull power when, for example, they execute a rapid return.

Freely chosen duty cycle decreased with each successive stroke as a result of decreased pull time (which we expected) and increased recovery time (which surprised us). The increased recovery time may reflect the requirement to dissipate the rower's momentum (which increases with increased pulling speed) and to reverse its direction to initiate the recovery phase. Thus, internal work associated with movement of the rower's center of mass may have two consequences: increased power delivered to the center of mass during the pull, as previously reported (6,16), and increased time required to stop and reverse the direction of the center of mass. Consequently, minimizing pull speed may benefit stroke power in two ways: by reducing the internal work, and by reducing the time spent in the recovery phase. These suggestions should be interpreted

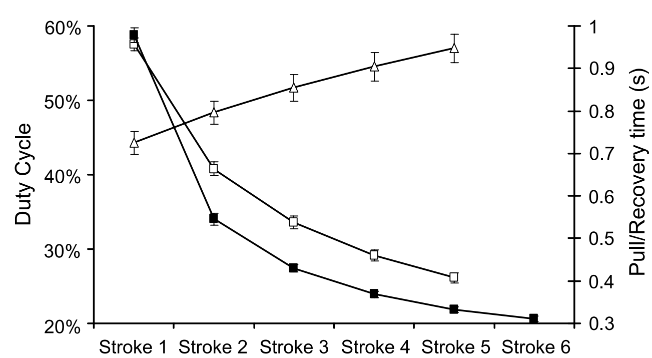

FIGURE 5—Duty cycle, pull time, and recovery time. Duty cycle (□) decreased significantly with each stroke. The decrease in duty cycle was attributable to significant decreases in pull time (■) and increases in recovery time (Δ). For all three measures, values for each stroke differed significantly from all other strokes.

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within the context of the present study, which is a study of maximal rowing power on a stationary ergometer. The extent to which our findings may aid in boat performance remains to be determined.

The peak instantaneous power values we observed, 41.9 $W \cdot kg^{-1}$, were substantially less than the values typically reported for maximal vertical jumping with two legs (52–72 $W \cdot kg^{-1}$ (3)) and occurred at a higher velocity (3.43 $m \cdot s^{-1}$) than the velocity of the body center of mass at the instant of peak power generation during maximal, countermovement, vertical jumping (2.48 $m \cdot s^{-1}$ (4)). The increased optimal velocity for rowing reflects the whole-body nature of rowing, which requires concomitant leg and back extension and arm flexion. The seemingly low power output of these highly trained rowers may reflect differences in vertical jumping and rowing, such as loading conditions and eccentric countermovement. Alternatively, it may indicate that the power required to accelerate the center of mass was not included in our measure of rowing power. Harrison (6) has reported that power delivered to the handle could be increased by up to 18% when subjects rowed a special ergometer that allowed their center of mass to remain relatively fixed. Similarly Martindale and Robertson (16) have reported that the energetic cost of moving the body ranged from 200 to 552 J per stroke during ergometer rowing, which would require up to 331 W (552 J at 36 strokes per minute, Table 4 of that paper). In the present study, we were primarily interested in rowing power output, which is inherently compromised by the requirement to accelerate body mass, and we did not attempt to account for internal work. In future studies, we may obtain kinematic measures to quantify that power requirement.

In this study, we have reported values and relationships for stroke power, pull power, and instantaneous peak power. Each of those measures may have separate physiological and performance significance. Stroke power will likely be the variable of greatest interest to rowers because it represents performance power during ergometer rowing. Pull power represents the average power during whole-body exercise and relates directly to stroke power, with the additional constraint of time lost for the recovery phase. That is, stroke power is dependent on pull power and duty cycle. Lastly, peak instantaneous power represents maximum muscular power and, thus, may be of more interest to exercise scientists who are interested in basic aspects of maximal neuromuscular function.

We chose a flywheel moment of inertia that allowed our rowers to reach maximum instantaneous power in the third or fourth stroke. In so doing, we were able to establish the ascending limb, apex, and descending limb of the peak instantaneous power–velocity relationship. Further, the cumulative pull time to maximum power was 2.97 ± 0.17 s, suggesting that our power–velocity relationships were not skewed by fatigue (18). Although the inertial load we used had those advantages, it compromised our ability to thoroughly define the stroke power–stroke rate relationship. Using a larger inertial load would have allowed us to obtain higher resolution of the stroke power–stroke rate relationship and might have allowed us to detect a greater stroke power value at around 40 strokes per minute (Fig. 4). An optimal inertia to define that relationship would have compromised our ability to fully describe the pull power–velocity and instantaneous power–velocity relationships. Having now determined those relationships, we plan to perform additional studies with larger flywheel inertia to carefully examine the stroke power–stroke rate relationship.

In summary, our data demonstrate that the rowing force–velocity relationships are essentially linear and that the pull power and instantaneous power–velocity relationships are curvilinear with maxima occurring at handle velocities of approximately 3.25–3.43 $m \cdot s^{-1}$. Of greater practical importance, our power–velocity relationships indicate that the rowers who participated in this study would reach maximum stroke power at 40 strokes per minute, and the differences in maximum pull power (1995 ± 67 W) and stroke power (812 ± 28 W) emphasize the importance of duty cycle. Put more simply, rowers only make power when they pull, and the more time they spend in the recovery portion of the stroke, the less average stroke power they will produce. Our adaptation of the inertial load method provided a valid and reliable method for determining maximal power and establishing the power–velocity relationship across a broad range of velocities on a rowing ergometer in one short exercise bout.

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