

Research article

Comparison of rowing on a Concept 2 stationary and dynamic ergometer

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Abstract

Biomechanical and physiological responses to rowing 1000 m at a power output equivalent to a 2000 m race were compared in 34 collegiate rowers (17 women, 17 men) rowing on a stationary and dynamic Concept 2 ergometer. Stroke ratio, peak handle force, rate of force development, impulse, and respiratory exchange ratio decreased by 15.7, 14.8, 10.9, 10.2 and 1.9%, respectively, on the dynamic ergometer. In contrast, percent time to peak force and stroke rate increased by 10.5 and 12.6%, respectively, during dynamic ergometry; the changes in stroke rate and impulse were greater for men than women. Last, VO_2 was 5.1% higher and efficiency 5.3% lower on the dynamic ergometer for men. Collegiate rowers used higher stroke rates and lower peak stroke forces to achieve a similar power output while rowing at race pace on the dynamic ergometer, which may have increased the cardiopulmonary demand and possibly reduced force production in the primary movers. Differences were more pronounced in males than females; this dichotomy may be more due to dynamic ergometer familiarity than sex.

Key words: Biomechanics, physiological response, stroke rate, efficiency, cadence.

Introduction

Competitive rowing is a year-round sport that typically includes the use of rowing ergometers for indoor training and as a means to assess fitness across time. Traditional ergometers are stationary; the rower moves relative to the resistance unit. To better simulate on-water rowing, manufacturers developed dynamic ergometers, in which part or all of the ergometer moves in response to the motion of the athlete. Subsequent research comparing dynamic and stationary ergometry to on-water sculling at fixed stroke rates is equivocal. Elliot et al. (2001) showed that dynamic ergometry and sculling elicited similar biomechanics, whereas Kleshnev (2005) observed shorter drive lengths and higher handle forces during ergometry than sculling. In contrast, in studies comparing dynamic and stationary ergometry at fixed work rates, lower stroke forces and higher stroke rates were observed during dynamic than stationary ergometry (Bernstein et al. 2002; Colloud et al. 2006). Despite the observed differences in rowing biomechanics across stationary and dynamic ergometers at fixed work rates, the physiological responses were similar (Bernstein et al., 2002; Mahony et al., 1999).

The aforementioned studies comparing stationary and dynamic ergometers or sculling and dynamic ergometry used the RowPerfect dynamic ergometer. Shortly after the appearance of the RowPerfect dynamic ergometer, Concept 2 developed a unique dynamic ergometer. On the RowPerfect dynamic ergometer, both the seat and foot

stretcher move on the main rail, whereas Concept 2 placed its stationary ergometer on “Slides” so that the entire unit moves relative to the motion of the rower (Figure 1). The moving mass on the Concept 2 dynamic ergometer (35 kg) is more than twice as large as the moving mass on the RowPerfect dynamic ergometer (17 kg). Given the design differences between the two models, it is uncertain if the findings from the studies comparing the RowPerfect stationary and dynamic ergometers are applicable to the Concept 2 counterparts. The primary purpose of this study was to compare the biomechanical and physiological responses of collegiate rowers rowing at a fixed power output representing their 2000m race pace on Concept 2 stationary and dynamic ergometers. Secondary purposes were to determine if there were differences between males and females and between novice and varsity rowers.

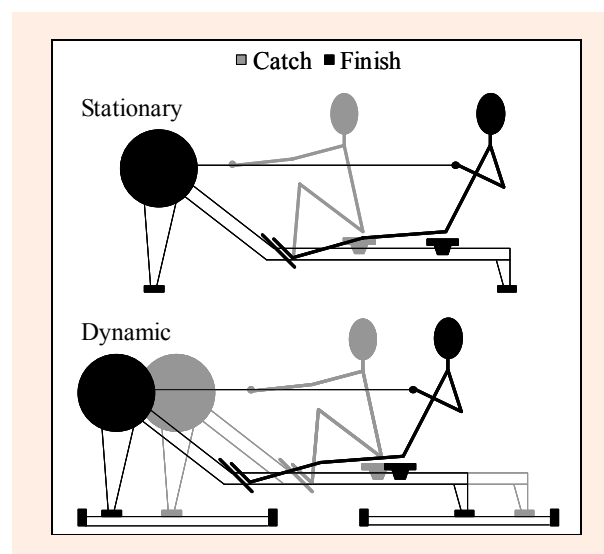


Figure 1. Diagram of the catch and finish positions on the stationary and dynamic Concept 2 ergometer.

Methods

Subjects

Forty-five Division III collegiate rowers gave their written informed consent, as approved by the Ithaca College Human Subjects Review Board, and completed the study during the last weeks of a spring rowing season. All rowers had used the Concept 2 dynamic ergometer during the fall and spring seasons of the current racing year; though, based on the coaches' qualitative assessment, the women's teams used the dynamic ergometer more so than the men and varsity athletes more so than novice athletes. Eleven of the rowers were excluded from subsequent data

Table 1. Descriptive subject data. Data are means (SD).

	Number	Age (y)	Height (m)	Mass (kg)	Experience (y)
Women	17	20.2 (1.2)	1.70 (0.08)	66.3 (8.20)	2.7 (1.8)
Novice	4	18.5 (0.6)	1.64 (1.00)	61.8 (7.90)	1.0 (0.0)
Varsity	13	20.7 (0.9)	1.71 (0.06)	67.7 (8.10)	3.2 (1.7)
Men	17	19.7 (1.1)	1.83 (0.07)	80.3 (9.20)	2.9 (2.5)
Novice	8	19.4 (0.9)	1.85 (0.08)	81.7 (10.2)	1.0 (0.0)
Varsity	9	20.0 (1.1)	1.82 (0.07)	78.6 (8.90)	4.7 (2.4)
Combined	34	19.9 (1.2)	1.76 (1.00)	73.3 (11.1)	2.8 (2.2)
Novice	12	19.1 (0.9)	1.78 (13.0)	75.0 (13.4)	1.0 (0.0)
Varsity	22	20.4 (1.0)	1.76 (0.08)	72.1 (9.80)	3.8 (2.1)

analysis for not maintaining a constant power output between the stationary ergometer (SE) and dynamic ergometer (DE) trials. Power output on the DE had to be within 2% of the power output on the SE. Accordingly, 34 rowers were included in the study, 17 women and 17 men split amongst 12 novice and 22 varsity rowers. Salient subject characteristics are presented in Table 1.

Protocol

Subjects completed two 1000 m trials at their 2000 m race pace on a Concept 2 Model C ergometer (Concept 2 Inc., Morrisville, VT). One trial was completed with the Concept 2 as a SE and the other with the Concept 2 as a DE. Using a counterbalanced design to eliminate order effects, 23 of the original subjects completed the DE trial first and 22 subjects completed the SE trial first. Warm-up on a DE, stretching, and rest between trials were allowed as desired.

Race pace was calculated by determining the power output for each subject based on his or her average 500 m split during a 2000 m ergometer trail. Subjects were instructed to maintain power output during their SE and DE trials at their pre-determined 2000 m race pace power output by watching the ergometer power display. Additionally, a researcher monitoring the power output on the display verbally cued the subject to hold power output steady if it started to fluctuate. The drag factor on the ergometer was set at 130 for all tests; drag factor setting affects the rate at which the flywheel decelerates. With higher settings, the flywheel decelerates more quickly, resulting in greater drag or required effort to achieve a particular power output.

Data collection and analysis

A 2200 N tension load cell (model #3190011, Bertec Corporation, Columbus, OH) mounted between the handle and chain of the ergometer was used to collect handle forces at 1000 Hz using DATAPAC 2K2 software (RUN Technologies, Mission Viejo, CA), an AM6100 amplifier (Bertec Corporation, Columbus, OH), and a PCM-

DAS16/330 A/D board (Computer Boards, Inc., Middleboro, MA). The load cell was calibrated by the manufacturer to 216.8 N/V and validated with known static weights. Handle forces were collected on 36 of the original 45 subjects due to data collection time constraints and load cell availability. Of these 36 subjects, only 28 maintained a power output on the DE within 2% of their SE power output. Subject characteristics of the 28 load cell subjects (14 men, 14 women; 11 novice, 17 varsity) are in Table 2.

From the raw force data, stroke rate, stroke ratio, impulse, peak force, time to peak force, and rate of force development were calculated for each stroke during the last minute of rowing. The catch of each stroke was identified as the point at which force increased above a 10 N threshold, and the finish was the point at which force dropped below 10 N. The drive phase was defined as the time between catch and finish. The recovery phase was defined from the finish of the drive to the next catch. Stroke ratio was calculated as recovery time divided by drive time. Impulse was the integral of force from catch to finish. Peak force was the maximum force recorded during each stroke. Time to peak force was the time in seconds from the catch to peak force. Time to peak force was also expressed as a percent of stroke time. Rate of force development was calculated by dividing peak force by time to peak force in s. The average of each variable was calculated across strokes from the last minute of rowing and used for all subsequent analyses.

The ergometer measured and stored the average power output and stroke rate for each trial. Since it takes two to four minutes to achieve a physiological steady state while rowing at a constant pace, the physiological data were also measured over the last minute, or at the end of trial, depending on the variable (Hagerman 1984). Expired gases were measured with a ParvoMedics TrueMax2400 metabolic cart (Consentius Technologies, Sandy, UT), which was recalibrated for every test. The cart used expired gasses to calculate VO_2 and the respiratory exchange ratio (RER) every five seconds; the 12

Table 2. Descriptive subject data for load cell subgroup. Data are means ($\pm$ SD).

	Number	Age (y)	Height (m)	Mass (kg)	Experience (y)
Women	14	20.2 (1.4)	1.73 (7.70)	69.0 (7.20)	3.1 (1.9)
Novice	3	18.3 (0.6)	1.67 (10.6)	64.6 (7.00)	1.0 (0.0)
Varsity	11	20.7 (1.7)	1.74 (6.40)	70.2 (7.10)	3.6 (1.0)
Men	14	19.4 (1.1)	1.83 (0.08)	79.7 (10.0)	2.8 (2.8)
Novice	8	18.6 (0.5)	1.81 (0.09)	78.3 (8.60)	1.0 (0.0)
Varsity	6	20.5 (0.5)	1.85 (0.08)	81.5 (12.3)	5.2 (2.9)
Combined	28	19.8 (1.3)	1.78 (0.09)	74.3 (10.1)	2.9 (2.3)
Novice	11	18.5 (0.5)	1.77 (11.0)	74.6 (10.1)	1.0 (0.0)
Varsity	17	20.6 (0.9)	1.78 (0.09)	74.2 (10.5)	4.2 (2.2)

Table 3. Means ($\pm$ SD) for power output (Watts) for all subgroups of subjects.

All Subjects	SE	DE	% Difference
Women (N = 17)	211.1 (4.3)	212.1 (1.0)	0.4 (0.7)
Men (N = 17)	334.0 (7.1)	334.8 (1.1)	0.2 (0.2)
Combined (N = 34)	271.0 (6.3)	271.7 (1.7)	0.3 (0.3)
Load Cell Subgroup	SE	DE	% Difference
Women (N = 14)	219.3 (4.6)	220.3 (4.60)	0.5 (0.7)
Men (N = 14)	325.9 (5.4)	326.4 (10.6)	0.2 (1.0)
Combined (N = 28)	272.6 (3.5)	273.4 (7.10)	0.3 (0.8)

SE: stationary ergometer group; DE: dynamic ergometer group.

samples preceding trial termination were averaged to obtain data for the final minute. Rowing efficiency ($W \cdot L^{-1} \cdot \min^{-1}$) was calculated by dividing the average power by absolute VO_2 from the final minute of a trial. Heart rate (HR) was tracked throughout a trial with a Polar F1 heart rate monitor (Polar Electro Inc., Lake Success, NY). The maximum HR observed during the final minute was recorded for data analysis. Immediately after each trial, participants rated total body and lower extremity rating of perceived exertion (RPE) on the modified BORG scale (1-10).

Statistical analysis

Power output was evaluated for the SE and DE trials of each subject. Subjects whose DE power output was not within 2% of their SE trial were excluded from the study and not used in the statistical analysis. Biomechanical and physiological variables were analyzed with a mixed model $2 \times 2 \times 2$ ANOVA (ergometer: stationary v. dynamic $\times$ sex: male v. female $\times$ experience: novice v. varsity) with repeated measures on ergometer at an α -level of 0.05. Significant interactions were explored using independent or dependent t-tests as appropriate. Sidak-Bonferroni adjustments were made to the alpha level for the multiple pairwise comparisons (Sidak, 1967). As suggested by Neter, et al. (1996), the number of pairwise comparisons depended on the specific interaction resulting in new α -levels of 0.0253 for two pairwise comparisons and 0.0127 for four pairwise comparisons. All analyses were performed with SPSS software (SPSS Inc; Chicago, IL).

Results

There were no differences between novice and varsity athletes for any of the measured variables, and thus all data were combined across experience level. Subsequent analyses used 2×2 ANOVAs with repeated measures on ergometer to compare differences across ergometer design and between men and women only. Row times were similar between the SE and DE, 220.9 ± 19.6 s and 220.6 ± 19.6 s, respectively. Accordingly, mean power outputs were also similar between SE (272.2 ± 72.2 W) and DE (272.9 ± 72.2 W). Effect sizes for all comparisons were extremely small ranging from 0.01 to 0.05 (Cohen 1969). Dependent t-tests with a Sidak-Bonferroni adjusted alpha level of 0.0083 for the six multiple comparisons revealed no significant differences (p ranging from 0.025 to 0.508) in power output for the SE and DE for all groupings of subjects. Power output for the men was 58% greater than for the women ($p < 0.001$). In the load cell subgroup,

power output for the men was 48% greater than for the women ($p < 0.001$). These differences decreased when power output was normalized to body mass, with men producing 31% and 28% more power per kg than the women for all subjects and the load cell subjects respectively ($p < 0.001$). Power outputs in Watts are presented in Table 3.

Biomechanical variables

The 28 rowers in the load cell analysis group were similar in age, height, mass, and years of experience as compared to the entire 34 rowers as determined with independent t-tests ($p > 0.278$ all variables). Moreover, there was no significant difference between experience level ($p = 0.752$) between the men and women of this subgroup; though, height and mass were significantly different between the 14 males and 14 females (independent t-tests, $p < 0.001$ both variables).

There was no difference ($p = 0.532$) in stroke rate, measured in strokes per minute (spm) between the men, 30.6 ± 3.2 spm, and women, 30.1 ± 2.4 spm. Stroke rate was 12.6% higher on the DE ($p < 0.001$); the change in stroke rate was greater for the men, 15.5%, than for the women, 9.8%, ($p = 0.026$). Stroke ratio was 0.34 lower on the DE than the SE ($p < 0.001$). Impulse and peak handle force were 67 and 36% greater for the men than women, respectively ($p < 0.001$ both variables). Both impulse and peak force were lower ($p < 0.001$ both variables) on DE than the SE, decreasing 10.2 and 14.8%, respectively. The drop in impulse, 44.6 N·s for the men and 21.1 N·s for the women, was greater for men than women ($p < 0.001$). Absolute time to peak force, expressed in seconds, did not change across ergometers ($p = 0.609$); however, when expressed relative to stroke time, percent time to peak force occurred 1.2% later in the stroke ($p < 0.001$) on the DE, $15.3 \pm 2.2\%$, than on the SE, $13.8 \pm 3.0\%$. Rate of force development (RFD) was 12% lower on the DE as compared to the SE ($p = 0.006$). Moreover, RFD was greater ($p < 0.001$) for the men, 3053 ± 726 N·s⁻¹, than for the women, 2196 ± 511 N·s⁻¹. Table 4 shows the biomechanical data and Figure 2 depicts the average force profiles separated by ergometer and sex.

Physiological variables

Table 5 shows the physiological data. Heart rate was 1.7% lower for males as compared to females ($p = 0.008$). Absolute and relative VO_2 were higher during DE than SE ($p \leq 0.017$); this difference resulted from the changes in the men, whose VO_2 was 0.24 L·min⁻¹ or 2.80 ml·kg⁻¹·min⁻¹ higher on the DE than SE ($p \leq 0.007$). There was no difference in VO_2 for the women between ergometers. The women did have lower absolute and relative VO_2 than

Table 4. Means ($\pm$ SD) for biomechanical variables for women and men on the Stationary (SE) and Dynamic (DE) Ergometer.

		Stroke Rate*	Stroke Ratio*	Impulse*† (Ns)	Peak Force*† (N)	Time to Peak (s)	Time to Peak* (% stroke)	RFD*† (N·s ⁻¹)
Women	SE	28.7 (1.3)	2.08 (.20)	273.0 (23.5)	654.2 (74.70)	0.29 (0.06)	13.9 (2.6)	2336 (586)
	(N=14) DE	31.5 (2.5)	1.80 (.27)	251.9 (27.7)	592.6 (77.10)	0.30 (0.05)	15.4 (2.1)	2055 (415)
Men	SE	28.4 (2.2)‡	2.25 (.25)	370.6 (39.9)‡	900.1 (109.8)	0.29 (0.06)	13.8 (3.4)	3238 (797)
	(N=14) DE	32.8 (2.5)‡	1.85 (.25)	326.0 (39.8)‡	792.5 (115.3)	0.28 (0.05)	15.2 (2.8)	2909 (633)

Note. *Statistically significant ($\alpha = 0.05$) difference between ergometers; † statistically significant ($\alpha = 0.05$) difference between sexes ($\alpha = 0.05$); ‡ male change from SE to DE greater than female change ($\alpha = 0.0253$).

the men on both machines ($p < 0.001$). Men were $8.3 \text{ W} \cdot \text{L}^{-1} \cdot \text{min}^{-1}$ more efficient than women on the SE ($p = 0.003$). Male efficiency dropped $2.3 \text{ W} \cdot \text{L}^{-1} \cdot \text{min}^{-1}$ on the DE relative to the SE ($p = 0.018$). Total body and lower extremity RPE were similar on the DE (7.5 ± 1.4 and 7.1 ± 1.5 , respectively) and SE (7.6 ± 1.0 and 7.4 ± 1.2 , respectively), and RER was 1.9% lower on the DE than the SE ($p = 0.016$).

Discussion

The primary purpose of this study was to compare the biomechanical and physiological responses of collegiate rowers at a constant 2000 m race pace power output on a Concept 2 stationary and dynamic ergometer. Stroke rate and percent time to peak force were higher at fixed workloads during dynamic ergometry than during stationary ergometry. In contrast, stroke ratio, impulse, peak force, and RER were lower during dynamic than stationary ergometry. Secondary purposes were to investigate differences between novice and varsity rowers and between male and female rowers. Males had overall higher power outputs accompanied by higher peak handles forces and impulses than the females.

The lack of effect of experience, novice v. varsity, observed in this study could be related to the end of the season data collection. One year of on-water and ergometry rowing may have sufficiently minimized differences in the physiological and biomechanical variables measured during SE and DE ergometry in the novice and varsity

athletes. Alternatively, it is possible that constraints of ergometry rowing minimize technique and physiological differences between novice and varsity rowers that may be present during on-water rowing.

Biomechanical variables

Stroke rates were similar on the stationary ergometer between males and females and increased an average of 12.6% on the dynamic ergometer when maintaining a fixed power output. The higher stroke rate observed on the Concept 2 dynamic ergometer is similar in magnitude to the increase previously measured on the RowPerfect dynamic ergometer relative to its stationary model (Bernstein et al., 2002). Stroke ratio also decreased 13.5 and 17.8% for women and men respectively during dynamic ergometry due to a drop in recovery time; drive time was similar for all subjects across ergometers (approximately 0.67 s). These results support findings that show increases in stroke rate are accomplished by decreases in recovery time (Dawson et al., 1998; Torres-Moreno et al., 2000).

The increase in stroke rate from stationary to dynamic ergometry in the current study was larger for men than women (15.5 vs. 9.8%, respectively). According to the coaches, the female rowers utilized the dynamic ergometers more frequently during practice than the male rowers. The additional training may have enabled the female rowers to apply force more effectively during dynamic ergometry, resulting in fewer strokes per minute to obtain their specified power output as compared to the men. The larger decrease in impulse for men (12.0%) on

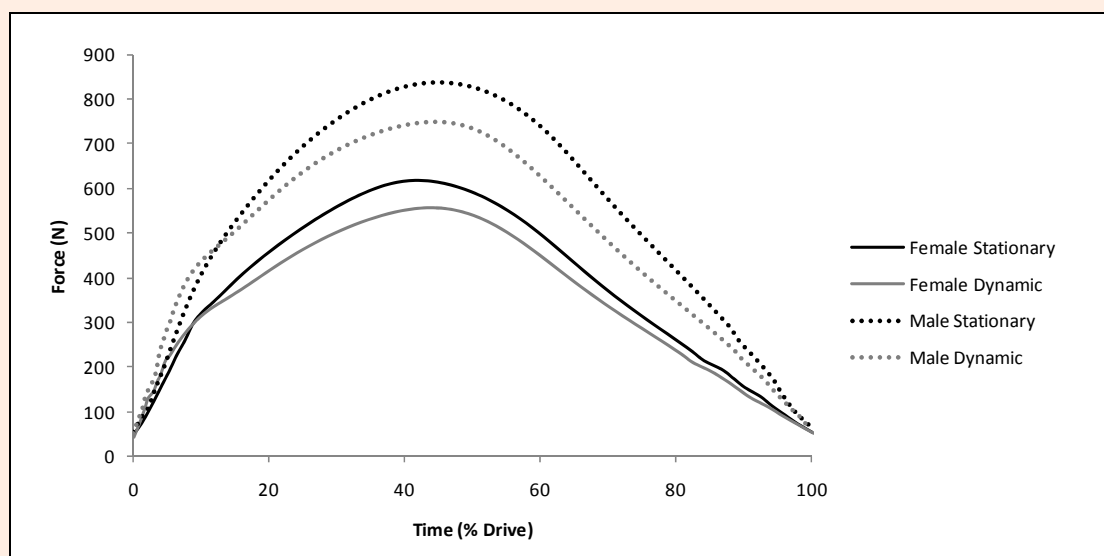


Figure 2. Normalized and averaged force-time profiles for women and men during the drive phase of the stroke on the stationary and dynamic ergometers.

Table 5. Means ($\pm$ SD) for physiological variables for women and men on the Stationary (SE) and Dynamic (DE) Ergometer.

		HR [†] (bpm)	Total Body RPE	Lower Extremity RPE	Absolute VO ₂ [†] (L·min ⁻¹)	Relative VO ₂ [†] (ml·kg ⁻¹ ·min ⁻¹)	Efficiency (W·L·min ⁻¹)	RER*
Women	SE	187 (4)	7.6 (1.0)	7.4 (1.0)	3.11 (0.31)	47.3 (4.6)	67.5 (4.60)‡	1.06 (0.06)
	DE	187 (6)	7.7 (0.9)	7.2 (1.0)	3.12 (0.30)	47.4 (3.5)	67.5 (5.50)	1.03 (0.04)
Men	SE	181 (7)	7.5 (1.1)	7.4 (1.3)	4.44 (0.58)#	55.5 (5.4)#	75.8 (10.6)#	1.06 (0.05)
	DE	184 (6)	7.3 (1.7)	7.0 (1.9)	4.68 (0.50)	58.3 (3.5)	71.8 (7.10)	1.05 (0.05)

Note. *Statistically significant ($\alpha = 0.05$) difference between ergometers; † Statistically significant ($\alpha = 0.05$) difference between sexes ($\alpha = 0.05$); # SE significantly ($\alpha = 0.0253$) different from DE within sex; ‡ Women significantly ($\alpha = 0.0127$) different than men within condition.

the dynamic ergometer than women (7.7%) substantiates this supposition. To maintain power output, the men's larger drop in impulse was counterbalanced by a greater increase in stroke rate on the dynamic ergometer, while the women, who had a smaller drop in impulse on the dynamic ergometer, did not have as large an increase in stroke rate. Due to the purported disparity in dynamic ergometry use by the male and female rowers in this study, the result may reflect additional experience on the dynamic ergometer as opposed to inherent sex differences.

Peak handle forces were also lower on the dynamic ergometer than on its stationary counterpart when rowing at fixed power outputs; these differences are consistent with changes seen on the RowPerfect dynamic ergometer relative to its stationary model (Bernstein et al. 2002; Colloud et al. 2006). Peak handle force data are similar to the handle force data observed during on-water rowing in an eight, which suggests that the Concept 2 dynamic ergometer approximates on-water rowing conditions in such boats (Ishiko et al., 1983; Zatsiorsky and Yakunin, 1991). The dynamic ergometer peak handle force and impulse data of the current study are, however, approximately 20% lower than those reported in a study of brief duration maximum rowing on a Concept 2 DE (Benson and Abendroth-Smith, 2004). The differences in impulse and peak force between the studies are expected given the different work tasks. The subjects in the Benson and Abendroth-Smith (2004) study, also Division III collegiate rowers, generated maximum power output in 20 strokes, whereas the subjects in the current study completed 1000 m pieces at their 2000 m race pace. The subjects in the 2004 study likely used stroke force to increase power output, as opposed to relying on stroke rate alone or a combination of stroke rate and stroke force, to maximize power output. Time to peak force, stroke ratio, and stroke rates were similar between the current study and the Benson and Abendroth-Smith (2004) study.

While absolute time to peak force was similar across ergometers in the current study, percent time to peak force increased from stationary to dynamic ergometer. More importantly, rate of force development was lower on the dynamic ergometer. The lower peak force and lower rate of force development are visually evident from the force-time profiles (Figure 2). Also apparent on the force curves, though not quantified, is a more drastic change in slope, or RFD, approximately 10% into the stroke cycle on the dynamic ergometer. This apparently steeper slope just following the catch transitioning to a lower RFD before peak force is consistent across rowers and has been observed in other studies for both on-water and dynamic ergometry rowing (Bernstein et al., 2002; Elliot et al., 2001; Martindale and Robertson, 1984).

Kleshnev and Kleshneva (1995) proposed that the absence of the change of slope between the catch and peak force on a stationary ergometer may be due to disparity between foot stretcher and handle forces. Alternatively, the subtle differences in RFD between the ergometers could be due to the smaller ergometer mass being accelerated on the dynamic ergometer, which is approximately 35 kg for the Concept 2. On the stationary ergometer, in contrast, the rower accelerates his or her body mass with each stroke, which was 69.0 ± 7.2 kg and 80.0 ± 10.0 kg for the women and men, respectively. The lighter mass may allow forces to be developed more quickly just after the catch and may better approximate the mechanics of on-water rowing, which may be advantageous for off-water training for competitive rowers.

Collectively, the biomechanical data reported in this and other rowing studies show that athletes pull more strokes per minute with less force per stroke on a dynamic ergometer compared to its stationary counterpart at a fixed power output (Bernstein et al., 2002; Colloud et al., 2006). The reduced force per stroke observed on the dynamic ergometer may reflect a decreased effectiveness at transferring propulsive force during dynamic ergometry. The force change requires rowers to pull more strokes per minute to maintain the same power output, which they do by decreasing recovery rather than drive time (Dawson et al., 1998; Torres-Moreno et al., 2000). All the aforementioned biomechanical differences allow dynamic ergometry to better simulate actual rowing or sculling (Elliot et al., 2001; Kleshnev, 2005).

Physiological data

The increased VO₂ and decreased efficiency on the dynamic ergometer for the men rowing at a fixed power output may be a consequence of the stroke rate change. Similar changes in VO₂ and efficiency or economy occur as cadence increases at various power outputs in trained to well-trained male cyclists (Chavarren and Calbret, 1990; Coast and Welch, 1985; Hagberg et al., 1981; Marsh and Martin, 1997; Nielsen et al., 2004; Takaishi et al., 1998). The VO₂ changes in the male subjects in the current study, however, contrast with data from an earlier rowing study, which showed that VO₂ was similar during incremental tests to exhaustion on a RowPerfect stationary and dynamic ergometer in elite male rowers (Mahony et al., 1999). The inconsistency in VO₂ data between the current study and Mahony et al. (1999) may be due to differences in subject fitness and dynamic ergometer familiarity. Indeed, VO₂ was similar across conditions for the female subjects in this study, who were more highly ranked than the male subjects, and, who like the subjects in Mahony et al. (1999), were more experienced on the dynamic ergometer. Data from cycling studies support the

hypothesis that subject fitness and dynamic ergometer experience affect VO_2 as stroke rate increases at a fixed power output. The cycling data show that VO_2 increases to a greater extent in less experienced and less fit males at higher cadences across various power outputs than it does in more fit and more experienced males (Marsh and Martin, 1993; 1997; Takaishi et al., 1998). A possible explanation for the 5.0% increase in VO_2 in the male rowers in this study during dynamic ergometry is that they had to increase internal muscular work to achieve the specified workload. Perhaps the males' relative inexperience with the dynamic ergometer required them to increase synergist and core muscle activation to produce the specified power output during dynamic ergometry. Data from cycling studies support this supposition and show that inexperienced males have higher muscle EMG as cadence rises across various power outputs than experienced male cyclists (MacIntosh et al., 2000; Takaishi et al., 1998).

The difference in RER between conditions in the subjects in this study was 1.9% with a small to moderate effect size of 0.3, suggesting a small but possibly meaningful change. RER values above 1.00, as seen in both conditions, indicate increased buffering of plasma lactate, and correspond to elevated levels of anaerobic metabolism in the working musculature (Brooks et al., 2000). The small but significantly lower RER on the dynamic ergometer relative to its stationary counterpart at a fixed power output suggests that anaerobic ATP production was reduced during dynamic ergometry, reflecting a possible decrease in metabolic activity in the primary movers, a supposition supported by the lower impulse and peak handle forces measured during dynamic ergometry.

Lower extremity RPE data are inconsistent with the aforementioned hypothesis. The most probable explanation for the lack of change across ergometers in lower extremity RPE specifically, and whole body RPE generally, is that the subjects based their perceived exertion primarily on intensity, which was similar across trials. Since the subjects trained regularly at that intensity, they probably had well-formed notions of how they should feel after a 1000 m work bout. In short, the sensitivity of the RPE scale may be insufficient to measure potentially small but significant changes as were observed in VO_2 and RER.

Collectively, physiological data show that the cardiopulmonary load was greater during dynamic ergometry at a fixed power output in some subjects; the data also suggest that anaerobic metabolic activity in the primary movers was reduced. These changes likely resulted from the higher stroke rates needed to produce the same power output while rowing on the dynamic ergometer. These findings are consistent with the literature on cyclists, which shows that greater exercise cadences reduce primary mover force production and increase aerobic demand (Chavarren and Calbret, 1990; Coast and Welch, 1985; Hagberg et al., 1981; Marsh and Martin, 1997; MacIntosh et al., 2000; Moritani and Muro, 1987; Nesi et al., 2004; Nielsen et al., 2004; Sparrow et al., 1999; Takaishi et al. 1998).

Together, the findings suggest that biomechanical and physiological changes occur in dynamic ergometry compared to stationary ergometry at constant power out-

puts. Decreases in peak handle force and impulse on the dynamic ergometer were accompanied by increases in stroke rate between ergometers. It is possible that some of these differences were a product of the experimental design, which allowed stroke rate to vary across ergometer as the subjects rowed at a constant power output. Consequently, in future studies comparing stationary and dynamic ergometers, scientists may wish to control both power output and stroke rate to determine if there are genuine differences in the biomechanical and physiological response between the two designs. Future studies should also examine stationary and dynamic ergometry under race conditions to determine if either ergometer results in a greater power output over a fixed distance and elicits different biomechanical adaptations and physiological responses. The biomechanical and physiological changes in this study may also have been influenced by experience and training time on the dynamic ergometer, which was not controlled. The larger changes in impulse and stroke rate accompanied by a larger increase in VO_2 and drop in efficiency for the males was confounded by the men being not as experienced with dynamic ergometry nor as accomplished rowers as the females. Thus, it is difficult to determine the root cause for the less effective force application and increased cardiopulmonary demand observed in the male subjects on the dynamic ergometer. Future studies should examine stationary and dynamic ergometry following a season of standardized training on the stationary and dynamic ergometers.

Conclusion

Collegiate rowers used higher stroke rates and lower stroke forces to achieve a similar power output on the dynamic Concept 2 ergometer than its stationary counterpart. These changes increased the cardiopulmonary demand in some rowers and possibly reduced force production in the primary movers. The differences were more pronounced in males than females; this dichotomy may be due to dynamic ergometer familiarity more than sex. These results have important implications for athletes training on Concept 2 stationary and dynamic ergometers. Depending on the athlete, stationary and dynamic ergometry may be equally useful for cardiopulmonary fitness, stationary ergometry may best improve force production, and dynamic ergometry may help rowers maintain their feel for the water with more similar force profiles and high stroke rates.

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This paper is dedicated to the memory of Julie Abendroth.

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Key points

- When rowing at a constant power output, all rowers used higher stroke rates and lower stroke forces on the Concept 2 Dynamic ergometer as compared to the Concept 2 Stationary ergometer.
- When rowing at a constant power output, cardio-pulmonary demand was higher for all rowers, as measured by heart rate, on the Concept 2 Dynamic ergometer as compared to the Concept 2 Stationary ergometer.
- When rowing at a constant power output, efficiency was lower for male rowers on the Concept 2 Dynamic ergometer as compared to the Concept 2 Stationary ergometer.

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