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Investigation of biomechanical factors affecting rowing performance

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Abstract

It was hypothesized that a crew's rowing performance was predictable based on their total propulsive power, synchrony (a real-time comparison of rower propulsive force magnitudes) and total drag contribution (a measure of the rowers' effect on shell drag forces during the recovery), quantities calculated from individual rower's force–time profiles and recovery kinematics. A rowing pair was equipped with transducers to gather shell velocity, propulsive blade force, oar angular position and seat displacement. Eight subjects (four port, four starboard) participated in two rounds of data collection. The first round pairings were random, while the second round pairings were assigned based on Round 1 results. Regression analysis and ANCOVA were used to test the validity of assumptions inherent in the predictive model and, if applicable, explore a linear model predicting rowing performance based on total propulsive power, synchrony and total drag contribution. Total propulsive power, synchrony and total drag contribution were correlated and further were affected by pairing, violating assumptions inherent in the linear model. The original hypothesis was not supported based on these violations. Important findings include (1) performance cannot be predicted using the simple linear model proposed, (2) rowers' force–time profiles are repeatable between trials, with some but not all rowers adapting their force–time profile dependent on their pair partner, presumably in an effort to increase the level of synchrony between the two, and (3) subtle biomechanical factors may play a critical role in performance.

Keywords: Power; Drag contribution; Synchrony

1. Introduction

The rowing system comprised of three major components: the rower, the shell and the oar. The force generated by the biological system, the rower, results in displacement of the total rower/oar/shell system through the action of the oar (Fig. 1). The rowing motion is continuous with a force generating phase, the stroke, and a gliding phase, the recovery, during which the rowers return to their initial position. The net result of the system equations of motion is that system velocity is dictated by the difference between the propulsive force applied and the drag forces acting on the system (Baudouin and Hawkins, 2002). Therefore a rower, both as an individual and member of a crew, should attempt to maximize their force input to the system while minimizing their contribution to drag.

Since rowing races are often decided by tenths of seconds, understanding how physical and biomechanical factors affect rowing performance is desirable. This investigation set out to develop a methodology to specifically quantify biomechanical factors and their importance in rowing performance. Explanatory factors were derived from system kinematics, rowing literature and rowing coaching philosophy.

Time to row a set distance is the ultimate metric of performance in rowing (Schneider and Hauser, 1981; Sanderson and Martindale, 1986; Smith and Spinks, 1995; Lazauskas, 1997) and therefore, maximizing average system velocity is critical. Average shell velocity, and equivalently system velocity over a length of time, is affected by total rower power (Schneider and Hauser, 1981), oar force (Ishiko et al., 1983) and isometric rowing strength (Secher, 1975) and is constrained by the

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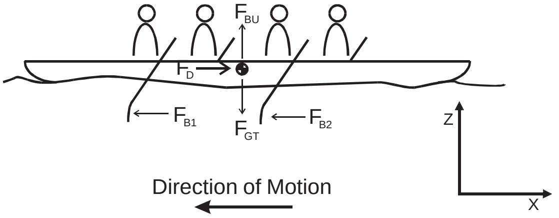

Fig. 1. Forces acting on the rowing system. The summed forces acting on the blade (F_{Bi}) of each individual rower (i) provide the sole propulsive input to the system and is countered by drag forces (F_D). Vertical equilibrium is established due to the balancing of gravitational (F_{GT}) and buoyant forces (F_{BU}).

drag acting on the system. Therefore, variables of the rowing system that affect propulsive power and/or drag forces should correlate with rowing performance.

Blade force, created by the interaction of the blade with the surrounding water, is the only source of propulsive force and power acting on the system (Schneider et al., 1978; Sanderson and Martindale, 1986; Baudouin and Hawkins, 2002). Oar force–time profiles, quantifying the resultant bending force applied to the oar over the duration of the stroke, are specific to a certain rower (Ishiko, 1971; Schneider et al., 1978) and repeatable (Ishiko et al., 1983; Wing and Woodburn, 1995), and can be combined with oar position/velocity data to quantify a mean power. Total crew power can be quantified (the sum of individual's mean power), and this value is expected to relate to rowing performance.

Forces exerted on the oars should be balanced to most efficiently displace a rowing shell, minimizing the net torque and drag forces acting on the system (Schneider and Hauser, 1981; Baudouin and Hawkins, 2002). A time-dependent comparison of blade force profiles provides a measure of crew synchrony. Though rowers' blade forces must differ slightly (~0%–10% depending on oar angle) in a pair to produce balanced torques on the boat, due to differences in the effective levers of the oars, crew synchrony should correlate with performance.

Drag forces constrain forward displacement of the system. Hydrodynamic drag is the dominant source of drag force on the rowing system, (Sanderson and Martindale, 1986; Lazauskas, 1997) primarily comprised of frictional force along the hull, i.e. skin drag (Millward, 1987). Power loss due to drag cannot be avoided, however it can be minimized. For optimum system energetics and performance the shell velocity should be maintained constant (Senator, 1981; Sanderson and Martindale, 1986; Smith and Spinks, 1995). The movement of the rowers causes the shell velocity to increase during the recovery due to conservation of momentum principles (Celentano et al., 1974; Dudhia, 2000). This dictates that a rower should strive to maximize the time spent on the slide (moving the seat towards the catch) over the duration of the recovery, thereby minimizing recovery velocity variations and the rower's contribution to drag and power requirements of the system (Smith and Loschner, 2002). A measure of the crew's contribution to drag due to non-optimized recovery kinematics, total rower drag contribution, is expected to explain variations in rowing performance.

This investigation set out to determine the dependence of rowing performance on the concepts introduced in this section by defining biomechanical variables representative of each concept, as supported by physical principles, rowing literature and rowing concepts. The following hypothesis was tested:

> Crew performance can be predicted from: (1) the total propulsive power developed by rowers, (2) the level of synchronization between rowers and (3) total rower drag contribution.

2. Methods

Rowing data were collected in a coxless pair (Pocock C-Shell, Concept2 Ultralight oars) during test sessions on the water. Eight subjects were recruited from the U.C. Davis varsity men's crew. All subjects read and completed the human research participant forms, as approved by the IRB at U.C. Davis. Subjects were tested during two separate water sessions. Four port and four starboard subjects participated in two rounds of data collection. The results from Round 1 trials (random pair assignments) were used to predict results from all possible remaining pairs of rowers. Round 2 pairings were based on these predictions, to test specific aspects of the hypothesis and to maximize the range of the explanatory variables. Data were collected during maximum sustainable effort rowing at 28–30 strokes/min. Stroke rate was monitored via a stroke watch during the trial and validated during data analysis. Three valid trials were analyzed from each pair, with an average of 8 (±1) consecutive strokes constituting a single trial.

Oar bending force was measured using two foil strain gauges (OMEGA SG-13/1000-LY11, 1000 Ω) glued on opposite sides of the oar shaft between the handle and the sleeve, 20 cm inboard of the sleeve, perpendicular to the plane of the oar blade, similar to previous studies (Ishiko, 1971; Schneider et al., 1978; Wing and Woodburn, 1995; Hill, 2002). The gauges were connected in a $\frac{1}{2}$-Wheatstone bridge, to allow for signal amplification and temperature compensation, and were calibrated to give normal blade force (0–700 N).

A one-turn linear potentiometer (LKG Industries No. PC23, 5 kΩ) was used to quantify the oar angular position. The potentiometers tracked the angle between the oarlock and the gunwale of the shell and were calibrated from +50° to −50°. Zero degrees represented the perpendicular, with positive angles indicating a displacement of the oar toward the bow of the shell. Oar angular position was compensated for flexion of the oar shaft under load, according to bending data collected during bench tests.

Rower center of mass location relative to the shell was modeled to move with the seat, whose displacement was measured using a compact linear position transducer (UniMeasure LX-PA-40-P1K-∗). The transducer was mounted on a cross-member affixed to the gunwales and the cable was attached to the seat. The potentiometers were calibrated over the possible range of motion of the seat (0–65 cm). Positive seat displacement indicated a forward displacement relative to the shell.

Shell velocity was measured using an impeller (Nielsen-Kellerman #151) attached external to the shell and an induction coil (Nielsen-Kellerman #3155) mounted perpendicular to the impeller shaft in the bow seat foot well. Calibration of the velocity measurement transducer was conducted by a series of tow tests. Shell velocity was monitored by measuring the time required to travel set distances while counting the number of impeller rotations over a 2–7 m/s range.

Data acquisition was completed using a PC-Card manufactured by National Instruments (DAQCARD-Al-16E-4) mounted in a laptop computer (Hewlett-Packard Pavilion notebook n5425) that was housed on the rowing shell. Outputs from the conditioning/amplification box on the shell connected directly to the PC-Card National Instruments LabView software (Version 6.0) was used to control the data acquisition process (1000 Hz sampling rate), write the data to file (text files) and filter the data (10 Hz Butterworth Low-pass).

The explanatory variables (total crew power, synchrony, drag contribution) and the dependent variable (rowing performance) were derived from the four measured quantities. Propulsive power created by the normal blade force was determined by summing incremental work (product of torque and angular displacement) over 50 equal time increments per stroke and dividing by the duration of the stroke (Eq. (1)) for each successive stroke. Values for each stroke were then averaged over the number of strokes in a trial to determine individual rower power, and then summed between rowers to determine total propulsive power.

$$P_{\text{Row}} = \sum_{i=1}^{n=50} [(\text{Torque}_i + \text{Torque}_{i+1})/2] (\Theta_{i+1} - \Theta_i)/(t_{i+1} - t_i), \tag{1}$$

where P_{Row} is the propulsive power for that rower (W), Torque_i is the adjusted torque about the oarlock at stroke percentage i ($\text{Torque} = F_\text{B}x$, where x is the distance from oarlock to blade center of pressure, adjusted for oar bending and propulsive direction) (N-m), Θ_i the the oar angular position at stroke percentage i (rad), and t_i is the time at stroke percentage i (sec).

Synchronization between the two rowers during the stroke was measured by calculating the ratio of starboard propulsive blade force and port propulsive blade force over 50 time increments. The number of time increments that the rowers were in synchrony (defined to be within the ratio range of 0.9–1.1) were calculated and presented as a percentage of total stroke duration. Drag contribution, capturing the relative drag force contribution associated with rower kinematics during the recovery, was determined by measuring the difference between a rower's recovery seat velocity and a theorized ideal seat velocity (seat displacement during the recovery divided by recovery duration), calculating the effect of this velocity difference on shell velocity by multiplying it by the rower/system mass ratio (conservation of momentum principles), estimating the difference in drag force (ΔF_D) acting on the shell due to this velocity difference (Eq. (2)) and averaging this force throughout the recovery. Rowing performance was determined by averaging the shell velocity over the duration of the trial.

$$\Delta F_\text{D} = \tfrac{1}{2}\rho C_{\text{Dw}} A_\text{w} \Delta V_{\text{shell}}^2, \tag{2}$$

where ΔF_D is the difference in drag force created by a rower's idealized vs. actual seat velocity (N), ρ is the density of water (1000 kg/m^3), C_{Dw} is the coefficient of drag (0.002345 as provided by Pocock Shells), A_w is the wetted area of shell (3.76 m^2 as provided by Pocock Shells), ΔV_{shell} is the difference in shell velocity resulting from a rower's non-idealized recovery seat velocity (m/s).

The hypothesis was first tested using an ANCOVA, to determine whether the developed explanatory variables accurately predict variations in rowing performance. This model included a factor PAIR, representing the rowers in the boat during that trial, to account for variability in the dependent variable not captured by the suggested explanatory variables. If the factor PAIR was found to be significant, it would indicate that the suggested explanatory variables are not good predictors of rowing performance. If PAIR was not significant, then a linear model could be tested to identify the importance of each explanatory variable on rowing performance. For this linear test to be performed, the explanatory variables should be independent and repeatable.

Since total rower power was based on individual rower power, rower oar force time profiles needed to be explored for repeatability. Rower oar force time profile repeatability (Ishiko et al., 1983; Wing and Woodburn, 1995) was quantified at 50 equivalent stroke completion points. Individual strokes were delineated by identifying changes in oar angular direction. A single increment of stroke completion was determined "repeatable" (measured between strokes in a trial, or between trials) if the standard deviation of the force magnitudes, normalized for peak force to reduce the influence of outlying values, was less than 10%. Rower repeatability was expressed as the percentage of "repeatable" increments within the total possible increments. Repeatability was assessed for successive strokes within a trial, between trials, and between pairings. The largest value of normalized standard deviation was also captured for each comparison.

3. Results

All eight subjects were heavyweight collegiate rowers with a minimum of two completed years of collegiate rowing. Subjects represented a variety of body sizes, height (1.83–1.98 m) and mass (81.6–103.4 kg) (Table 1).

Rower repeatability within trials ranged from 78 to 100%, with variations ranging from 5.5% to 13.2%. However, repeatability between trials was 100% (within the 10% variation criterion) for all subjects (Table 2) supporting and quantifying the conclusions made by earlier investigators that rowers are capable of reproducing their force–time profiles (Ishiko et al., 1983; Wing and Woodburn, 1995; Hill, 2002).

Summed mean rower power for the eight pairs ranged from 1274.7 to 1938.7 W, average of 1628W±203W (Table 3). The values for power are comparable to values drawn from Smith and Loschner (2002) but higher than the values presented by Schneider and Hauser (1981). Propulsive blade force values, from which the power values are derived, fall within the same range presented by previous investigators (Celentano et al., 1974; Schneider et al., 1978; Smith and Loschner, 2002). Peak propulsive rower power occurred between 23% stroke completion for port rower #1 (P1) to 51% for starboard rower #4 (SB4), with five out of eight rowers applying peak force from 41% to 49% of stroke completion. Oar angular displacement averaged 88.6±3.2° over the 0.954±0.052 s required to complete the strokes.

Table 1
Subject data

	Height (m)	Weight (kg)	Age (years)	Rowing exp. (years)	Training level (number/ week)
Mean	1.90	87.3	21.8	3.50	3.75
Std. dev.	0.05	7.4	1.0	1.93	0.71
Minimum	1.83	81.6	20.0	2.00	2.00
Maximum	1.98	103.4	23.0	7.00	4.00

Descriptive statistics for the eight heavyweight collegiate subjects are presented. Rowing experience recorded complete years of rowing experience, with a minimum of two collegiate years required. Training level is presented as the number of on the water training sessions per week.

Table 2
Between trial and pair repeatability

Rower/ pair	Avg. force (N)	Repeat b/ w trials (%)	Largest var. b/w trials (%)	Repeat b/ w pairs	Largest var. b/w pairs (%)
P3				100	5.6
Pair P3S2	183.1	100	4.1		
Pair P3S4	190.7	100	5.8		
S2				100	7.2
Pair P3S2	163.3	100	4.2		
Pair P4S2	190.5	100	4.7		
P1				80	15.6
Pair P1S4	209.1	100	3.9		
Pair P1S1	185.4	100	5.4		
S4				100	5.2
Pair P1S4	173.0	100	7.1		
Pair P3S4	175.0	100	2.6		
P2				90	12.4
Pair P2S1	169.2	100	5.8		
Pair P2S3	190.6	100	6.7		
S1				100	4.3
Pair P2S1	162.9	100	4.2		
Pair P1S1	160.2	100	3.4		
P4				100	5.5
Pair P4S3	243.4	100	3.8		
Pair P4S2	234.0	100	3.4		
S3				100	7.1
Pair P4S3	162.6	100	5.1		
Pair P2S3	170.4	100	7.8		

The largest variation and the level of repeatability (10% criterion) occurring in a rower's force–time profile between trials and between pairs are presented. The average propulsive blade force is also shown to demonstrate scaling of strokes.

Rower synchrony ranged from 45% for pair P3S2, trial 3, to 4% for pair P4S3, trial 5, with an average value of 24±11% (Table 3). Variations in synchrony were dominated by differences in rower propulsive blade force, as timing differences contributed a maximum of 6.7% of the synchrony value.

Summed rower drag contribution averaged 1.85±0.38 N and was highest for pair P4S3, 2.65 N, and lowest for pair P2S1, 1.13N (Table 3). Peak rower recovery velocities ranged from 1.20 m/s for S3 to 1.67 m/s for S2. Instantaneous shell velocity ranged from 6.18 m/s, pair P1S4, to 2.57 m/s, pair P2S1. Average shell velocities ranged from 5.44 to 4.58 m/s (pairs P4S3, P2S1) with a mean value of 5.12±0.24 m/s. Interaction between seat and shell velocities can be seen in Fig. 2.

The ANCOVA demonstrates that the factor PAIR was significant and of the three covariates, only summed drag contribution was significant (Table 4). The *R*-squared value for average shell velocity with summed power, rower synchrony and summed drag contribution were 0.805, 0.489 and 0.401 respectively. A regression based correlation matrix demonstrated high correlations

Table 3
Data collection results

Pair/trial number	Number of strokes	Stroke rate	Avg. shell velocity (m/s)	Rower sync. (%)	Rower power (W)		Summed power (W)	Drag cont. (N)		Summed drag cont. (N)
					SB	P		SB	P	
P3S2										
3	7	28.1	5.07	45	740.8	776.8	1517.6	0.835	0.751	1.59
4	9	29.1	5.15	32	703.4	792.6	1496.0	1.070	0.969	2.04
6	9	29.8	5.34	34	746.2	814.6	1560.9	1.110	1.087	2.20
Average	**8.3**	**29.0**	**5.19**	**37**	**730.2**	**794.7**	**1524.8**	**1.005**	**0.936**	**1.94**
P1S4										
1	7	29.3	5.28	18	807.6	951.9	1759.6	0.819	0.791	1.61
2	8	29.1	5.33	22	795.2	979.6	1774.9	0.848	1.047	1.90
7	9	26.3	5.10	14	794.4	913.1	1707.5	0.619	0.667	1.29
Average	**8.0**	**28.2**	**5.24**	**18**	**799.1**	**948.2**	**1747.3**	**0.762**	**0.835**	**1.60**
P2S1										
1	6	26.7	4.64	34	685.8	608.6	1294.3	0.762	0.660	1.42
3	6	25.9	4.58	35	659.2	595.9	1255.1	0.475	0.650	1.13
Average	**6.0**	**26.3**	**4.61**	**35**	**672.5**	**602.3**	**1274.7**	**0.619**	**0.655**	**1.27**
P4S3										
1	7	31.8	5.38	5	720.7	1119.7	1840.5	1.207	1.121	2.33
4	8	32.5	5.41	6	647.3	1150.2	1797.6	1.403	1.243	2.65
5	8	31.4	5.44	4	687.9	1181.7	1869.6	1.312	1.172	2.49
Average	**7.7**	**31.9**	**5.41**	**5**	**685.3**	**1150.6**	**1835.9**	**1.307**	**1.179**	**2.49**
P4S2										
5	9	28.4	5.27	15	873.1	1080.1	1953.1	0.716	0.797	1.51
8	9	28.6	5.22	18	878.4	1077.6	1955.9	0.810	0.978	1.79
10	9	28.1	5.35	25	866.8	1040.2	1907.0	0.762	0.832	1.59
Average	**9.0**	**28.4**	**5.28**	**19**	**872.7**	**1065.9**	**1938.7**	**0.763**	**0.869**	**1.63**
P3S4										
5	9	28.5	5.25	26	823.1	781.5	1604.6	0.899	0.918	1.82
9	9	28.5	5.12	31	824.6	774.2	1598.8	0.871	1.024	1.90
10	9	27.6	5.11	27	813.5	809.7	1623.2	0.816	0.778	1.59
Average	**9.0**	**28.2**	**5.16**	**28**	**820.4**	**788.5**	**1608.9**	**0.862**	**0.907**	**1.77**
P1S1										
1	8	29.1	4.90	33	680.1	742.8	1422.9	0.831	1.068	1.90
8	7	27.2	4.84	39	674.0	764.9	1438.9	0.642	0.957	1.60
10	9	28.4	4.88	26	662.8	757.9	1420.7	0.800	1.028	1.826
Average	**8.0**	**28.2**	**4.87**	**33**	**672.3**	**755.2**	**1427.5**	**0.758**	**1.018**	**1.78**
P2S3										
0	8	28.8	5.05	23	727.7	750.2	1477.9	1.053	1.109	2.16
1	7	28.1	5.01	19	721.9	800.4	1522.3	0.917	1.045	1.96
8	9	28.0	5.05	23	819.0	830.2	1649.3	1.052	1.104	2.16
Average	**8.0**	**28.3**	**5.04**	**21**	**756.2**	**793.6**	**1549.8**	**1.007**	**1.086**	**2.09**

The descriptive variables of interest to the exploration of the hypothesis are presented for each trial for each pair. Pair PXSY represents the pairing of port rower X and starboard rower Y. Power and drag contribution are presented both for the individual and for the pair. Only summed values were used in the statistical analysis. The number of strokes sampled and stroke rate are also presented. Only two valid trials were collected for pair P2S1 due to collection difficulties.

between the explanatory variables and the dependent variable, and high levels of correlation between each other. Only the correlations of summed power and summed drag contribution (p-value of 0.325) and rower synchrony and summed drag contribution (p-value of 0.122) were not significant.

Actual results from Round 2 did not match well with the predictions based on Round 1 results. Pair P4S2 demonstrated a high summed power but had a larger synchrony value than expected (Table 5). Pair P3S4 was expected to have a high synchrony and medium summed power, and while their summed power was in the middle of the data set, their synchrony fell below the expected values. Similar differences were observed for pairs P1S1 and P2S3.

4. Discussion

The high correlation levels, lack of significance of total propulsive power and synchrony and the significance of the factor PAIR indicate that the hypothesis fails as stated. Rowing performance cannot be predicted based on the linear model proposed. The result that PAIR is significant indicates that the rowers in the boat are a more important variable when measuring rowing performance than the three derived variables and suggests a dependence of rowing data, and accompanying conclusions, on the subjects being studied. The lack of significance of total propulsive power and synchrony in the model together with PAIR and total drag contribution indicate that the variables chosen may not be ideal. Further, the high level of correlation of the variables indicated a lack of independence of the terms. The small range of the dependent variable (rowing performance) could impair the exploration of trends in the explanatory variables, especially with the higher than expected correlations. The results of the statistical analysis were anecdotally supported by the difference between predicted Round 2 results and actual results. Therefore, an exploration of the level of dependence of rowing performance on the explanatory variables was not initiated. However, this investigation provided key results in the following areas.

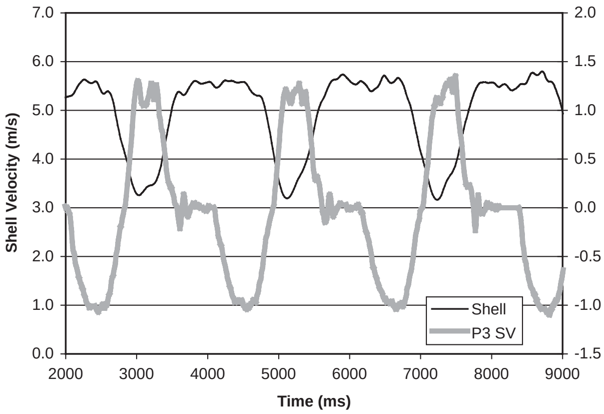

Fig. 2. Seat velocity vs. shell velocity. Shell velocity (Shell) and rower seat velocity (P3 SV) data were shown for three consecutive strokes for rower P3 during trial 5 with partner S4. The interaction between rower velocity (positive indicates movement toward bow) and shell velocity are shown.

Table 4
ANCOVA results

	β	p-value
PAIR		0.011
Summed power	0.00174	0.515
Synchrony	0.000252	0.803
Summed drag contribution	0.0404	0.007

The coefficient estimates (β) and p-values for the explanatory variables of the ANCOVA model are shown. Variables PAIR and summed drag contribution were found to be significant in the model (p-value 0.011 and 0.007, respectively).

Rower repeatability during and between trials was quantified and demonstrated to support qualitative conclusions from previous investigations (Ishiko, 1971; Ishiko et al., 1983). While rower repeatability ranged from 78% to 100% within the trials, rower repeatability between trials was 100% for all rowers (Table 3) with a largest between trial variation of 7.76%. It is apparent that poor strokes affected the within trial measurements (Fig. 3), however when averaged values were compared between trials, the impacts of these strokes were minimized and rowers demonstrated a higher level of repeatability.

Two rowers were shown to visibly alter their force–time profiles dependent on their partner. This result was unexpected as Wing and Woodburn (1995) demonstrated that three rowers in an eight were unaffected by the exchange of a fourth rower. The timing of the peak propulsive blade force for rower P1 shifted from 360 N at 23% of the stroke with partner S4 to 313 N at 44% of the stroke with partner S1 (Fig. 4). A similar change in rower P2's profile occurred when rowing with S1 or S3 (Fig. 4). The changes in shape of the profile were repeatable and sustainable during each pairing, indicat-

Table 5
Round 2 predicted vs. actual results

	Summed power (W)		Synchrony		Summed drag contribution (N)	
	Predicted	Actual	Predicted (%)	Actual (%)	Predicted	Actual
P4S2	1881	1939	2	19	2.18	1.63
P3S4	1594	1608	35	28	1.70	1.77
P1S1	1621	1427	15	33	1.45	1.78
P2S3	1288	1550	34	21	1.96	2.09

Data used to select the pairs for the second round of testing, based on the results from the first round, is presented alongside the actual results from these pairs.

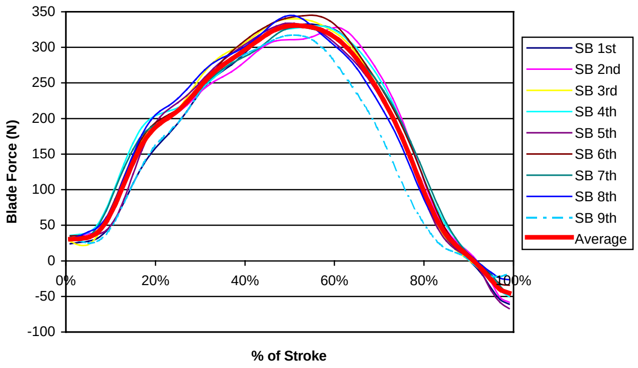

Fig. 3. Force–Time profiles for S4, pair P1S4, Trial 7. Variability is shown from stroke to stroke. This chart represents a within trial repeatability of 100%, and a largest variation of 8.26%.

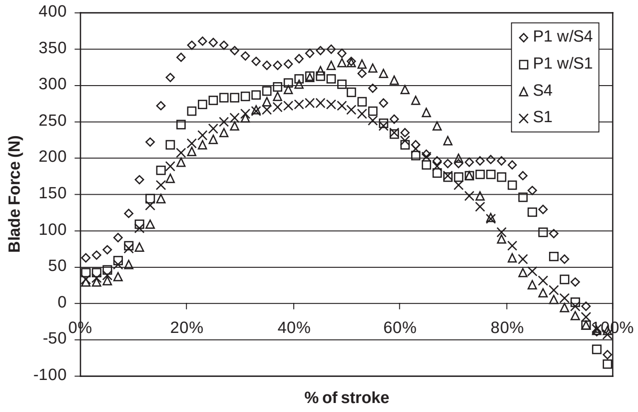

Fig. 4. Average force–time profiles for subjects P1 and P2. Data shown represent averaged force–time profiles for rower P1 paired with rower S1 and S4 and for rower P2 paired with rower S1 and S3. Averaged force–time profiles are also shown for subjects' partners in the pair (S4 and S1, S1 and S3, respectively). Timing of the peak propulsive blade force for P1 shifted from 360 N at 23% of the stroke with partner S4 to 313 N at 44% of the stroke with partner S1. The initial peak in rower P2's profile evident with partner S1 is not visible with S3 and there is a decrease in peak force from 344 to 318 N.

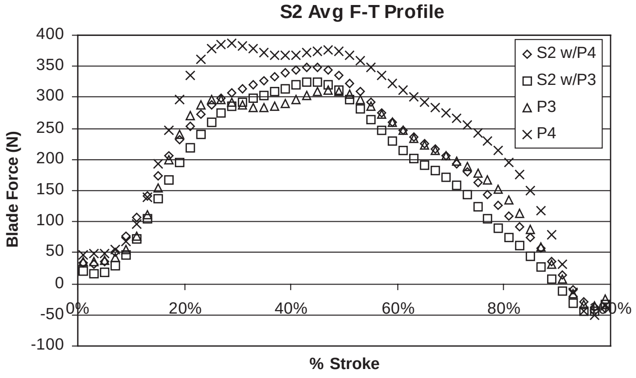

Fig. 5. Average force–time profiles for subject S2. Data shown represent average force–time profiles for rower S2 paired with rower P4 and P3. Averaged force–time profiles are also shown for rowers P4 and P3 while rowing with S2 in the pair. A change in magnitude is visible between S2's profiles dependent on the partner.

ing the changes were not due to fatigue or equipment difficulties. Alterations to rower's force–time profiles with different partners indicate the need to better understand interactions between the athletes.

This conclusion is further supported by the finding that rower S2 demonstrated a noticeable increase in force production over the entire length of the stroke when paired with P4 compared to P3 (Fig. 5). Although the largest variation in force-time profiles for subject S2 was only 7.2% (Table 3), a deviation of $>5\%$ was maintained for 48% of the stroke duration, signifying a distinct shift in force production by rower S2.

All three rowers' changes resulted in increased synchrony between the second pairings. This alludes to rower's responding to feedback within the rowing system and adapting their biomechanics as deemed appropriate. This adaptation occurred after only a brief warm-up period, indicative of an immediate, as opposed to learned, response from the rowers. Adaptability between long-term rowing partners has previously been discussed (Hill, 2002), and has been linked to both physiologic changes (Roth et al., 1993) and rowing experience (Smith and Spinks, 1995). The motivations and mechanisms of this adaptation should be better understood to increase a rower's ability to perform at high levels in different situations.

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