MECHANICAL ENERGY VARIATIONS IN ROWING

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A THESIS SUBMITTED IN PARTIAL FULFILMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF PHYSICAL EDUCATION

in

THE FACULTY OF GRADUATE STUDIES

School Of Physical Education And Recreation

We accept this thesis as conforming

to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

December 1982

Department of Physical Education, 1, December, 1982

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Date:

Abstract

The purpose of this study was to quantify and contrast the instantaneous segmental and total body energy patterns of rowing a single sculls racing shell with rowing a Gjessing (Norway) rowing ergometer, and to contrast energy savings through exchanges of mechanical energy among segments and conversions of energy within segments. Four scullers, two male and two female, were filmed at three stroke rates while rowing on a Gjessing rowing ergometer (RE), the RE mounted on a wheeled cart, and rowing in single sculls racing shells. Digitized coordinates of joint markers were combined with estimated body segment inertial parameters, and evaluated with link-segment methods after digital filtering to remove digitization noise. Mechanical energy and internal work analysis allowed calculation of energy savings due to exchange and interconversion of segmental energy.

The internal work was least in the wheeled RE and greatest in the boat. Saving of energy through exchange was greatest in the boat, and least in the stationary RE. Saving of energy through interconversion was greatest in the wheeled RE. The interconversions (expressed as a percentage of total work) were lower, and quite similar for both the boat and the stationary RE. Similarity of energy saving scores between the boat and the wheeled RE allow the conclusion that rowing ergometer testing might permit athletes to work at stroke rates more similar to racing levels.

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Acknowledgement

I wish to thank Dr. D. Gordon E. Robertson for the guidance and patience he has provided me in the preparation of this thesis. The patience and encouragement of the members of my thesis committee, Dr. K. D. Coutts, Dr. D. C. McKenzie, and Mr. B. Klavora were important in my carrying through with this paper to the completion. The encouragement of my classmates and of my friends on the University rowing crew are also gratefully acknowledged.

INTRODUCTION

Testing oarsmen's physiological capabilities with off-water rowing simulators is not new. Henderson and Haggard (1925) report use of an hydraulic rowing simulator to test the 1924 Yale University rowing crew. Hagerman and co-workers, in several studies (1971, 1972, 1975a, 1975b, 1978, 1979) have reported physiological testing of several hundred oarsmen since the early 1970's using the Lyons (Gamut Engineering, Redwood City, California) rowing ergometer. The Canadian Amateur Rowing Association uses Gjessing rowing ergometers (hereafter referred to as RE) (E. Gjessing, Plast. rekonstr. avd., Hospitalet Betanien, Bergen, Norway) to test Canadian oarsmen in their training for national rowing teams.

The Lyons ergometer simulates "sweep" rowing, in which the oarsman handles one oar on one side of the boat. An oarsman accustomed to rowing on one side of the boat is at a disadvantage when he is tested on a Lyons-type RE built for people accustomed to the other side of the boat; scullers, accustomed to rowing with two oars in a symmetrical motion are at a disadvantage as well.

The Gjessing RE is a "center-pull" machine. All sweep oarsmen are at a similar (slight) disadvantage on this machine, as the handle does not pivot about a point at either side of the boat. Instead, the handle is guided straight backwards and forwards by a bar attached to the "oar" handle. Scullers are at the least disadvantage on the Gjessing machine, as they need only alter their arm motion, while sweep-oar rowers must adapt by removing the normal twist and lean of their bodies from their rowing stroke. The chief disadvantage to the Gjessing RE is that it is difficult to row at normal racing stroke rates for more than a few minutes, while it is necessary to row a racing shell for 6 to 7.5 minutes to complete most races (striking between 32 and 40 strokes per minute, usually, depending on the race).

An RE capable of simulating the rowing motion and of simulating the work output requirements of race rowing is a valuable tool for use in team selection, training, and in technical coaching. The present Gjessing machine affords an approximation of the rowing motion. Current practise in the Canadian rowing community is to test oarsmen for 6 minutes on a Gjessing RE with a resistance of "3 kp" (approximately 29.4 N) applied to each flywheel revolution. The oarsman does "3 kp.m" or 29.4 J of work for each flywheel revolution. These "rows" are usually done with stroke rates between 26 and 29 strokes per minute; use of higher rates often result in the oarsman performing poorly because of excessive fatigue in the second half of the test. Lower stroke rates than 24-26 (depending upon the size of the rower, the larger, stronger rowers do very well at the low end of this continuum) result in poorer scores because the flywheel's revolution rate drops too much between strokes, and excessive effort is spent to return the flywheel to a "comfortable" speed. It would be valuable to the rowing community if the reason(s) for the difficulty in rowing at the stroke rates experienced in normal racing could be defined, so that the Gjessing RE could be redesigned to simulate the feel of rowing more accurately than it does now. Prior to any design changes, however, it is necessary to study the rowing machine in comparison with real rowing to assess existing differences between rowing the Gjessing machine and the boat.

Purpose

The purpose of this study was to quantify and contrast the instantaneous segmental and total body mechanical energy patterns of rowing in a single-sculls racing shell with rowing a Gjessing RE, and to contrast energy savings through exchanges of mechanical energy among segments and conversions of energy within segments.

METHODS

Subjects

Subjects included 2 male scullers and 2 female scullers. One of each of the male and female scullers were experienced in international competition. The other two subjects were significantly less experienced in race sculling. Before any testing or measuring each subject was informed of the nature of the study and consented to participate. Basic information about the subjects is in Table 1.

Table 1. Age, height, and body mass of subjects and masses of racing shells used in rowing trials.

Subject	Sex	Age	Height (cm)	Mass (kg)	Boat Mass (kg)
1	m	23	187.5	85.4	17.6
2	m	20	197.0	90.5	22.5
3	f	22	168.5	64.5	20.1
4	f	23	173.5	65.7	20.1

Procedures

Subjects were filmed rowing in single sculls racing shells for several rowing stroke cycles at stroke rates at, above, and below their normal racing rates. Rowing trials took place at the Burnaby Lake Canada Games (1973) rowing course. On a separate occasion, subjects were filmed rowing a Gjessing rowing ergometer (RE) at similar stroke rates to those used in the rowing trials. All filming was done using a motor-driven Locam 16 mm camera (Redlake Industries). All filming was at 25 frames per second (f/s).

Markers. Markers were placed at the ankle (lateral malleolus), knee (lateral femoral epicondyle, about 2 cm superior to the joint line), hip (greater trochanter of femur), shoulder (acromion process), elbow (lateral epicondyle of the humerus), wrist (spinous process of the ulna), and neck (posteriorly, on the spinous process of the first thoracic vertebra (T1)). The opening of the outer ear was used as a marker for the head.

All markers were placed on the subjects' right side and all rowing was done with the subjects facing the right of the camera's image, following the convention of having the subject face the positive x-axis of a normal Cartesian coordinate system.

Before all water trials, markers were placed 3 m apart on the port side (the side nearest the camera) of the subject's racing shell. Before the ergometer trials, two markers were placed on the RE to identify motion of the RE. Subjects' body masses were measured with a scale accurate to within 50 g or with a Kistler force plate.

Rowing Session. Subjects were prepared for their film trials after rowing workouts (within 40 min). When ready, subjects waited in the appropriate racing lane (lane three of the Burnaby Lake course, about 57 m from the camera), about 250 m to the right of the camera. The subject started to row, and was told of his stroke rates so that he could adjust his tempo to equal that chosen for the trial being rowed at the time. The subject's stroke rate was checked with a calibrated "rate watch" just before his or her passing the camera.

Ergometer Sessions. Subjects were permitted to row the RE until they felt comfortably "warmed up". When ready for filming, subjects started rowing the machine and used about six to eight strokes to attain their designated stroke rates, after which the rates were estimated with a stopwatch. The stroke rate was adjusted or maintained as required. When the subject was rowing at the correct tempo, floodlights were turned on, and the camera was run for the time required to complete about 3 complete rowing cycles. During the filming, the stroke rate was checked as accurately as possible to make sure that the subject maintained the correct rate throughout the trial. After each trial the subject rested momentarily. The filming was repeated at the other stroke rates.

The RE trials were repeated with the RE mounted on a wheeled cart. Manufacturer's specifications for the Gjessing RE are such that the machine is mounted on wheels aligned with the longitudinal axis of the ergometer. The CARA-owned machine has no wheels.

Data Collection and Analysis

Films were projected onto a digitizing table one frame at a time. The cartesian coordinates of all markers in each frame were "digitized" with a Numonics Graphics Calculator interfaced with a microNova computer (Data General Corp.). One full stroke cycle of each trial was digitized (catch-to-catch). Programmes used later in the data processing required that 6 frames before the beginning of the stroke and 6 frames after the end of the stroke were digitized. Data were then transmitted to an Amdahl 470/V8 computer for error checking, kinematic, and energy quantification.

Perspective error in the coordinate data, caused by the camera position being such that the movement was not perpendicular to the optical axis of the camera, was removed with a matrix transformation adapted from that described in Woltring (1975, 1976). Data were then smoothed by two passes (one forward and one backward to eliminate phase-shift) of a low-pass digital filter using a 5 Hz cutoff frequency for the ergometer data. Data for the boat trials were filtered using 2.5 Hz as the cutoff for the digital filter to retain as much of the "signal" as possible while reducing high frequency noise. The digital filtering method of reducing "noise" in film coordinate data has been validated by Pezzack, Norman, and Winter (1977). Anthropometric data for each subject were taken from tables provided by Dempster (in Winter, 1979b), based on subject weight.

Link segment analysis of the film data gave the instantaneous (frame-by-frame) linear and angular displacements, velocities and accelerations of the segments; energies and rates of change of mechanical energies of all segments and of the total body were calculated. Energies of all segments were calculated assuming that all segments returned to the same position at the completion of each stroke. In this situation, there is no net external work done on the body or by the body, as there is no change from stroke to stroke in the height of the body or in its velocity.

Segmental Energy. Energies of the segments and of the total body were calculated as described by Winter, (1979a). The energy of each segment (E_s) was calculated with the formula:

E_s = Potential energy (E_p)

+ Translational kinetic energy (E_{kt})

+ Rotational kinetic energy (E_{kr})

$$= mgh + 1/2\ mv^2 + 1/2\ I\omega^2 \qquad (1)$$

where
- m = segment mass in kg
- g = gravitational acceleration (9.8 m/s^2)
- h = height of segment mass centre in m
- v = absolute velocity of the segment mass centre in m/s
- I = rotational moment of inertia of the segment in $kg.m^2$
- ω = rotational velocity of the segment in rad/s.

Total Body Energy. The instantaneous energy of the total body (E_t) was calculated by summing the energies of all of the segments in each film frame:

$$E_t = \sum_{s=1}^{B} E_s \qquad (2)$$

where
- B was the number of segments and,
- E_s was the total energy of segment s in each film frame.

Internal Work. Calculation of the total internal work in the rowing stroke required inclusion of internal and external work. A concentric (shortening) muscle contraction is said to do positive work on a segment, increasing the total energy of that segment; an eccentric (lengthening against the contraction caused by some external moment) contraction is said to do negative work, dissipating mechanical (kinetic) energy and decreasing the total body energy (Winter, 1979a). Since rowing is usually done on a flat or nearly flat surface (i. e., with no appreciable current) there should be little if any change in the mechanical energy of the system from one stroke to the next. The system does change its draft and horizontal velocity during a stroke, but at steady pace rowing the changes are repeated every stroke. The boat and rower return to the same height and velocity and thus to the same mechanical energy at corresponding points of consecutive strokes. In previous studies of mechanical energy (e. g., Pierrynowski, et al., 1980, 1981) total energies have been found to vary slightly at corresponding stages of cyclic movements (walking and loaded walking). The slight change between finishing energy (E_{tn}) and starting energy (E_{t0}) appears as external work (W_t) due to movement of the total body or changes in its movement:

$$W_t = \sum_{i=1}^{N} \Delta E_{ti}$$

$$= E_{tn} - E_{t0} \qquad (3)$$

In this study it was presumed that there was no change in total energy (thus no W_t) between corresponding points of consecutive strokes. This constrained all segmental energy components to return to their original levels at the end of each stroke. W_t, then, accounted for external work done in the trial, and was subtracted from the total energy of the stroke prior to calculation of the exchanges among or interconversions within segments. "This correction assumes that the total body begins and ends at the same energy level and this is true across many..." strokes unless the subject is changing his or her average velocity with each stroke (quotation from Pierrynowski, 1978).

The total internal work (W_i) (defined by Winter, 1979a) of the sculling stroke was calculated by taking the sum of the absolute changes of the total body energy (ΔE_t) over the number of frames of the stroke (N). This calculation determined internal work assuming that energy can be both interconverted and exchanged where interconversion of energy within a segment implies conversion from potential energy to kinetic energy or vice-versa, and exchange of energy implies the transmission of mechanical energy from segment to segment.

$$W_i = -W_t + \sum_{i=1}^{N} |\Delta E_{ti}| \qquad (4)$$

The total work required assuming that there was energy exchange among segments but no interconversion of energy within segments (W_e) was given by:

$$W_e = -W_t + \sum_{i=1}^{N} \sum_{s=1}^{B} |\Delta E_{si}| \quad (5)$$

Total work if there was neither exchange nor interconversion (W_n) was calculated by summing the absolute values of the changes in the segmental energy components over the number of segments (B) and over the number of frames (N) in the movement:

$$W_n = -W_t + \sum_{i=1}^{N} \sum_{s=1}^{B} (|\Delta E_{psi}| + |\Delta E_{ktsi}| + |\Delta E_{krsi}|) \quad (6)$$

It is possible to use the three values W_n, W_i, and W_e to calculate the amount of energy "saved" or "preserved" in the motion by interconversion of, or exchange of mechanical energy. The appearance of these exchanges or conversions of mechanical energy reduce the need for the muscles to absorb energy in one place while generating energy in another. Energy saved (c. f., "conserved" Winter, 1979b) due to interconversions within segments (S_i) was calculated as the difference between the work allowing neither exchange nor conversion (W_n) and the work allowing exchange but no conversion (W_e). The amount of energy saved through interconversions within segments is expressed as a percentage of the total work that would have been required if no energy had been converted or exchanged (W_n) (i. e., if muscles were needed to generate or absorb all energy changes, and no conversion of energy occurred).

$$S_i = 100 (W_n - W_e) / W_n . \quad (7)$$

Energy saved due to exchanges among segments (S_e) was calculated as the difference between W_n and the internal work allowing exchange and transfer (W_i). This figure was expressed as a percentage of W_n:

$$S_e = 100\ (W_e - W_i)\ /\ W_n . \qquad (8)$$

The change in energy of the total system (body and boat) from its lowest value just before the catch to its highest value just before the finish may be used to derive the average power of the drive phase of the stroke. The data for the total energy of the system was scanned, and the scores for the lowest and highest mechanical energies were recorded, with their respective times. The average drive power (P_d) was calculated as:

$$(\text{highest M. E.} - \text{lowest M. E.})/\Delta\text{time} \qquad (9)$$

where -

Δtime was the elapsed time of the energy change

The average velocity ($\underline{v}$) during the stroke was calculated as:

$$(\text{displacement, catch to catch})/\Delta\text{time} \qquad (10)$$

where -

Δtime was the time required to complete the stroke from catch to catch.

RESULTS AND DISCUSSION

Cinematography

Boat Trials. A field of view of approximately 20 m in the movement plane was required to permit filming of at least one complete stroke cycle (catch-to-catch or finish- to-finish) and ten frames before and after the cycle's end points. The projected images could not be enlarged to more than about 3 % of life size due to the limited span of the digitizer, about 55 cm). Wells and Caldwell (1982) report the root mean square of the differences between filtered and unfiltered film data (RMSD) as an indication of digitization noise. The RMSD increased as the ratio of true size to image size increased. The largest such ratio experienced by Wells and Caldwell (1982) was about 16:1, while the same ratio for the data for the rowing trials in this study was about 34:1. RMSD was greatest in the x-coordinate of the ankle (23±4 mm, mean± 1 standard deviation) and least in the y-coordinate data for the boat (11±2) mm). The RMSD in most of the rowing data were similar to or slightly greater than that of Wells and Caldwell, using images approximately one half of the size found in the previous study. This similarity, using images as small as 3 % life-size suggests that the accuracy of the digitization was of sufficient accuracy to permit discussion of mechanical energy with respect to the rowing trials.

Ergometer Trials. The true size to image size ratios in the RE trials were about 9:1 for all trials; the RMSD of the film data in this case was less than 5 mm for all of the marker coordinates. The x-coordinate of the ankle marker again showed the greatest variability (average RMSD = 4.2±1.2 mm). This small RMSD in the RE film data suggests that the digitization of the RE trials was accurate.

Trials were assigned codes to identify the data for the analysis. "RB1A1," for example, refers to Rowing, Boat, subject 1, stroke rate "A" (a low stroke rate - "B" implies a medium rate, and "C" a high rate), trial 1. A "W" was used to denote wheeled RE trials, and "S" was used to denote trials using the stationary trials.

Stick figures of the movements of a subject rowing on the stationary RE and on the wheeled RE are presented in Figures 1A and 1B, respectively. Note that the subject's body translates on the ergometer while the RE does not move (c. f. the "ankle" position in Fig. 1A). On the wheeled RE, however, the subject's body translates very little, and the RE is moved (c. f. the nearly stationary "hip" and the moving "ankle" positions in Fig. 1B).

Internal Work

All internal work measures (W_i, W_e, W_n) were greatest in the rowing trials and least in the wheeled RE trials (Tables 2 to 4). The major differences between work scores in rowing trials and in ergometer trials were due to the differences in the translational energy of the test devices. These translational energies were greatest in the rowing trials because the system of rower and boat moved several metres during each stroke; these movements occurred at changing velocities

DRIVE PHASE OF ROWING A STATIONARY ERGOMETER

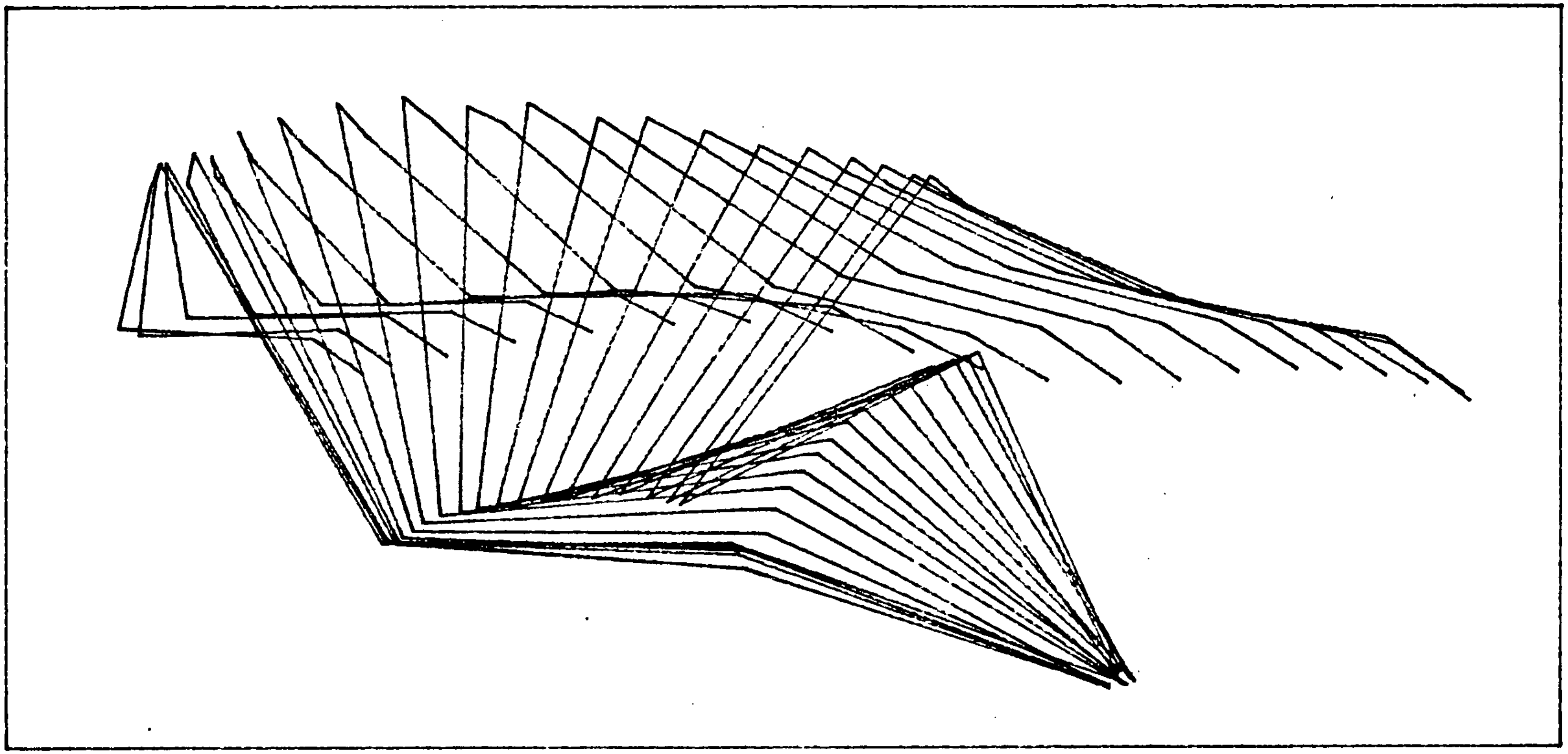


FIGURE 1 A.

DRIVE PHASE OF ROWING A WHEELED ERGOMETER

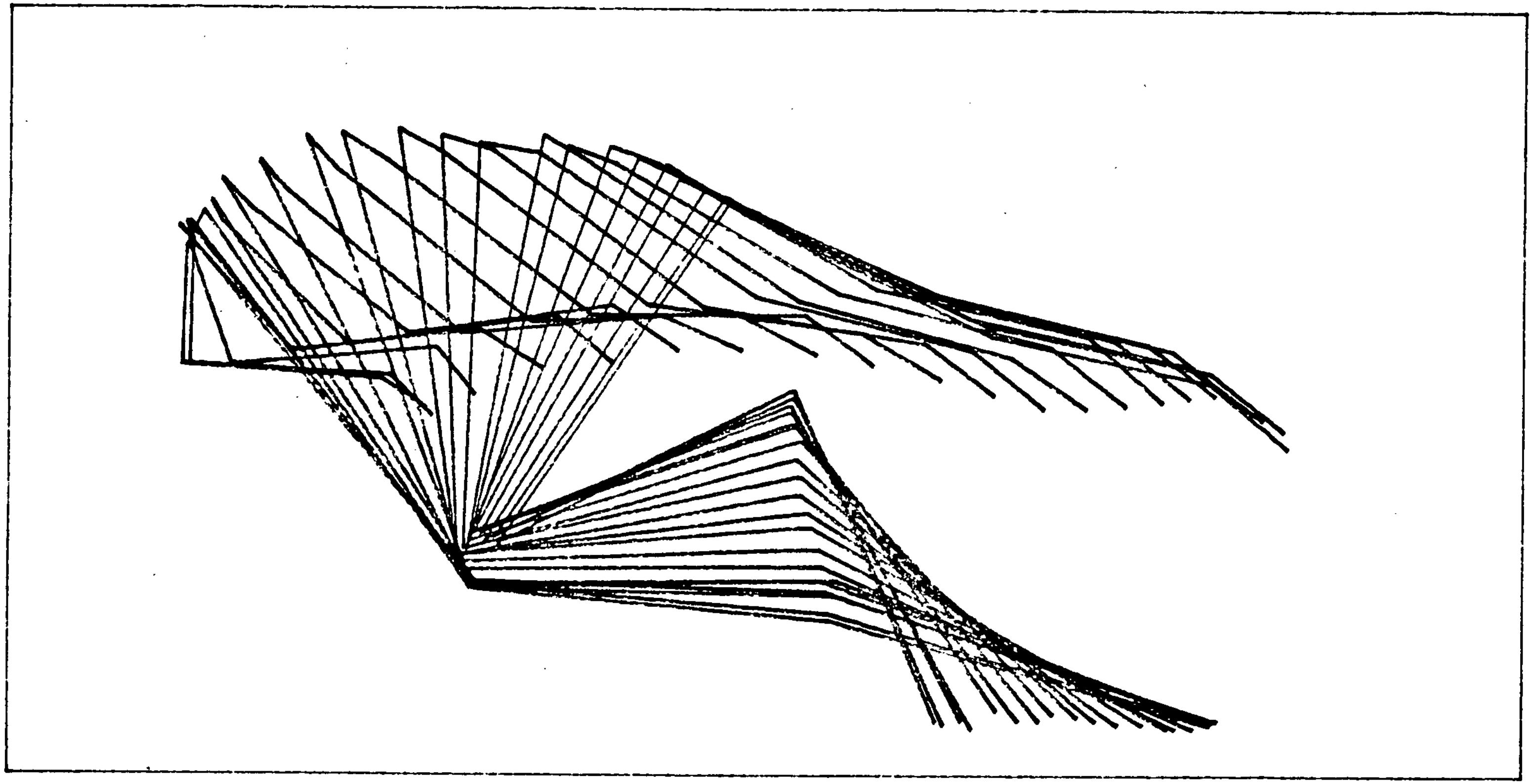


FIGURE 1 B.

Table 2. Internal work (joules) and energy savings (percent) for the sculling trials.

Subject	W_i	S_e	S_i	Trial Code
	832.2	27.6	18.7	RB1A1
1	1153.1	27.6	13.5	RB1B2
	970.7	38.1	14.8	RB1C3
	1657.6	22.8	15.0	RB2A1
2	1267.6	36.4	9.9	RB2B2
	1655.2	19.5	12.2	RB2C3
	594.0	32.1	16.8	RB3A1
3	909.6	32.3	11.6	RB3B2
	788.2	33.1	15.0	RB3C3
	696.2	27.0	15.7	RB4A1
4	756.1	31.0	13.8	RB4B2
	794.4	40.4	12.3	RB4C4
MEAN	-------	30.6	14.2	
SD		6.1	2.4	

Table 3. Internal work (joules) and energy savings (percent) for the wheeled RE trials.

Subject	W_i	S_e	S_i	Trial Code
	245.6	31.2	17.7	RW1A1
1	280.9	29.0	16.9	RW1B2
	336.5	24.7	15.3	RW1C3
	310.7	28.8	19.5	RW2A1
2	314.0	25.2	21.7	RW2B2
	335.3	25.5	18.0	RW2C3
	213.3	22.3	17.3	RW3A4
3	211.7	30.0	11.8	RW3B5
	212.0	32.6	16.1	RW3C6
	181.0	23.3	22.6	RW4A1
4	193.4	21.4	22.4	RW4B2
	236.0	17.6	21.8	RW4C3
MEAN	------	26.0	18.9	
SD		4.5	3.3	

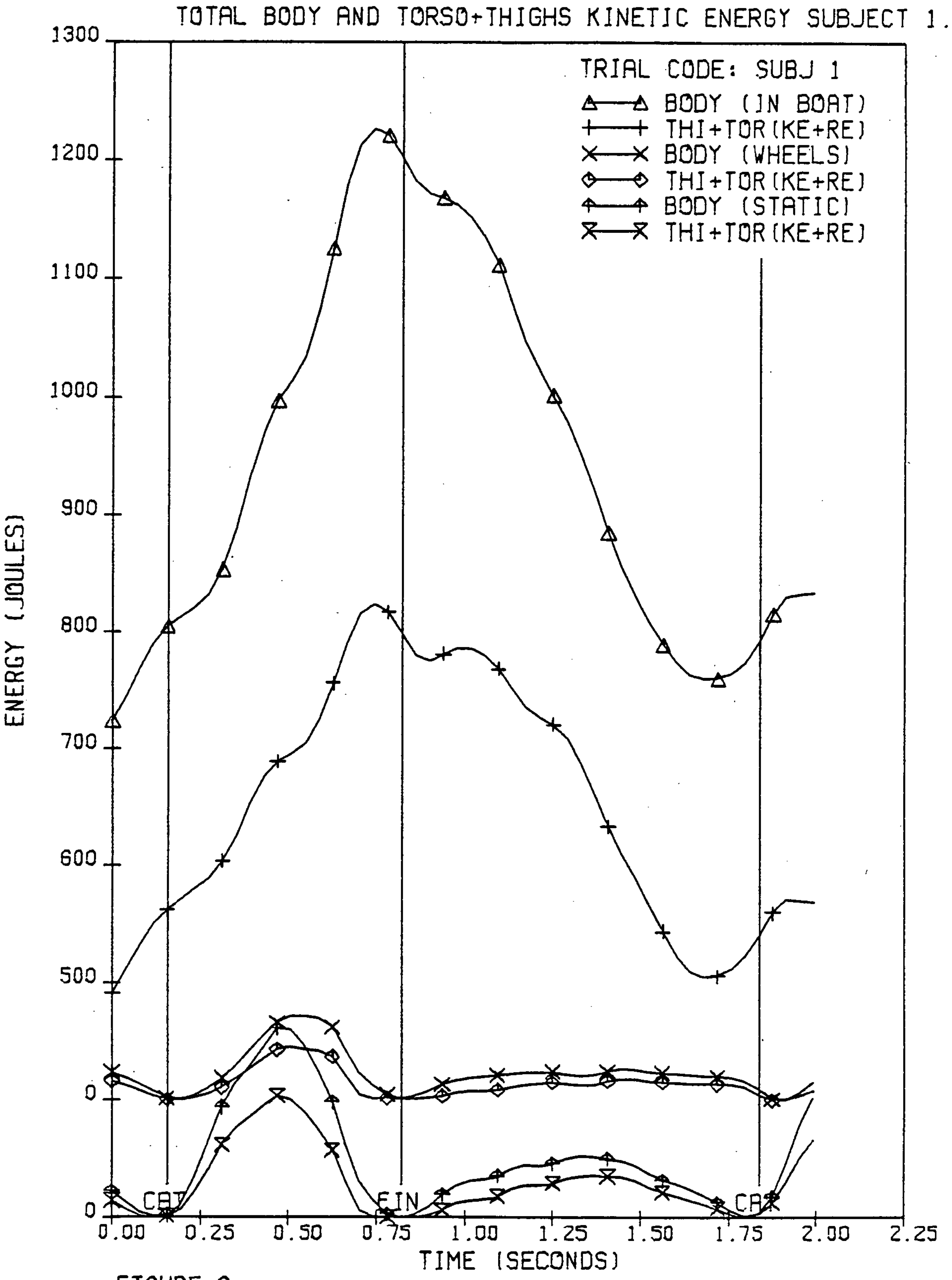
Table 4. Internal work (joules) and energy savings (percent) for the stationary RE trials.

Subject	W_i	S_e	S_i	Trial Code
	361.4	24.1	13.0	RS1A4
1	367.9	23.0	11.8	RS1B5
	551.9	11.9	8.2	RS1C7
	468.8	22.2	11.2	RS2A4
2	353.6	30.1	18.2	RS2B5
	458.6	24.3	11.4	RS2C6
	233.0	25.4	13.2	RS3A1
3	265.4	22.6	10.6	RS3B2
	256.8	28.7	12.6	RS3C3
	199.7	29.2	16.2	RS4A4
4	282.4	20.7	14.1	RS4B5
	320.3	16.0	15.5	RS4C6
MEAN	-----	23.2	13.0	
SD		5.3	2.7	

within the strokes. In the RE trials there was very little movement of the body other than that on the slide. With no movement of the RE relative to the external environment (as exists in the boat), there was no measure of the change of energy of the system of subject-RE that was probably reflected in the changes in the angular velocity of the flywheel of the RE. Motion of the RE in the wheeled trials was not great enough to cause significant changes of energy in the system of subject and RE.

The different internal work variables enumerate changes in the components of the energies of the segments. The curves shown in Figure 2 show the kinetic energies of selected energy variables at the same stroke rate on the different devices. The top curve demonstrates the greater changes in the total mechanical energy of the subject in the rowing trials. The W_i term is made up of the frame-by frame changes in the total body energy, of which the top curve in Figure 2 lacks only the potential energy (which is essentially a bias, in rowing) of the entire system and the energy of the boat. In the rowing trials, the changes in the energy of the system (the work) reflect the subjects' efforts to move the boat through the manipulations of the oars. The magnitude of the changes in energy through the drive, coupled with the duration of the drive (i. e., power) reflect the effectiveness of the rowing motions. These powers are discussed later in this paper.

The internal work values seen in tables 2 to 4 may be compared with internal work scores between 48.5 and 251.7 for level walking (Winter 1979a). Pierrynowski, <u>et al.</u>, (1980),



TOTAL BODY AND TORSO+THIGHS KINETIC ENERGY SUBJECT 1.
TRIAL CODE: SUBJ 1
BODY (IN BOAT)
THI+TOR(KE+RE)
BODY (WHEELS)
THI+TOR(KE+RE)
BODY (STATIC)
THI+TOR(KE+RE)
ENERGY (JOULES)
TIME (SECONDS)
1300
1200
1100
1000
900
800
700
600
500
0
0
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
CAT
FIN
CAT

FIGURE 2.

found work values in treadmill walking which averaged 165.7 (W_i), 340.2 (W_e), and 500.9 (W_n); values for internal work carrying a variety of external loads during treadmill walking ranged from 328 to 423 (W_e) (Pierrynowski, _et_ _al._, 1981). These researchers were able to include the speed of the treadmill belt in their investigations, to give an estimate of the "velocity" of their subjects motions. Such a measure was not possible during the present study, as the equipment available, and time and financial constraints prevented development of and adequate measure of the angular velocity of the flywheel during the RE trials. Scores for W_i in the boat trials in the present study were considerably higher than scores for the walking trials in these other studies.

The work data for the stationary RE are slightly higher than for the wheeled RE. The reason for this is apparent in comparing Figures 1A and 1B and in the bottom sets of curves in Figure 2. The lack of motion in the stationary RE causes the subject to have to accelerate and decelerate most of his body at each end of the stroke in addition to moving the RE's oar handle through the stroke. This is not like rowing a boat, in which the boat moves with the rower, and allows the subject to move the boat (which weighs about 20-25% of the subject) relative to himself, instead of all of the subject's motions being absolute with respect to the environment. i.e., The subject's movements in a shell cause the boat to change its velocity relative to both the subject and the external reference system, while the immobility of the stationary RE forces all of the subject's motions to be relative only to the external system of reference since the frame of the RE does not move perceptibly in response to the subject's actions. The general shape of the bottom sets of curves in Figure 4 is due to the need for the subject to come to a complete stop at each end of the slide. After stopping the movement of the drive, the subject was then required to accelerate his entire body in the opposite direction for the recovery. The high peak of the subject's energy during the drive was due to the velocity with which the subject moved during the drive. The lower peak in the energy of the system in the recovery was due to the subject performing essentially the reverse of the drive phase, but more slowly.

With no measure of the flywheel's instantaneous rotational velocity there is no clear way to compare the internal work in the ergometer conditions with the internal work in the rowing trials. The effect of the rower's movements on the boat are evident in the instantaneous changes in the velocity of the system. The angular velocity of the flywheel would reflect these efforts in the ergometer, and could be used to give energy values which could be used to compare the internal work scores of the different test devices. Future research in this area must include such a measure.

Energy Exchanges and Interconversions

Calculating savings of energy by exchange and interconversion avoids the problem of comparing internal work scores by permitting the comparison of the proportional differences between the "work" values. Energy savings calculated from Equations 7 and 8 are presented in the second and third data columns of Tables 2, 3, and 4. The S_e and S_i values are expressed as percentages of the total mechanical work if neither exchange nor conversion of energy are permitted.

The energy exchange term (S_e) may be used to discuss some of the differences between rowing and rowing ergometers. A larger proportion of the total apparent "work" (W_n) appears to be transmitted from the body to the device in sculling than in either RE condition, with visible effect on the shell. This is apparent from the larger S_e scores in the sculling data (Table 5). That the S_e in the wheeled RE was greater than the S_e in the stationary RE but less than that in the boat, and that the only real difference between the two RE conditions was the motion of the RE (refer to Figure 1 A and B) during the stroke reinforces this suggestion. As well, subjects claimed that the wheeled RE "felt" slightly more like real rowing than did rowing the stationary RE.

Interconversion of energy within segments (S_i) was greatest in the wheeled RE and was very similar for the sculling and the stationary RE data. The main source of the difference in estimated S_i may have been the presence or absence of large amounts of translational energy changes in the segments. In the wheeled RE most of the motion of the thighs and lower legs segments, for example, was either rotational or translational in the vertical direction only. With the stationary RE and with

Table 5. Power in drive, average velocity, stroke rate and average power.

	Trial Code	Drive Power (W)	Average Vel. (m/s)	Stroke Rate (/min)	Average Power (W)	Est. 2000 m Time
	RB1A1	377	3.75	25.6	161	8'53"
*	RB1B2	859	4.57	32	459	7'18"
*	RB1C3	962	4.74	32	514	7'02"
	RB2A1	462	3.66	20.4	157	9'07"
	RB2B2	434	3.87	24.1	174	8'37"
*	RB2C3	757	4.42	32	404	7'32"
	RB3A1	309	3.51	24.7	127	9'29"
	RB3B2	468	4.07	29.5	230	8'11"
	RB3C3	655	4.21	32	350	7'55"
	RB4A1	521	3.72	26	226	8'57"
	RB4B2	566	4.21	30.7	290	7'55"
	RB4C4	560	4.59	36.6	343	7'15"

the rowing shell, there was a large horizontal translational component to the motion in addition to the rotational and vertical movement components. Thus the chief difference between the stationary and the wheeled conditions is due to the computation of the S_i which, as a percentage of the total apparent change in energy, is increased in the wheeled RE because of the absence of the relatively large horizontal components seen in the motions of the subject in the stationary RE and boat trials.

There was no apparent relationship between the percentage of energy saved in the three devices and the stroke rate. Although there was an insufficient number of subjects to warrant inferential statistics, the differences between the means shown in Tables 2 to 4 are worth note. The mean S_e for the boat was significantly different from the values for both ergometer conditions ($t=2.14$, $p \leq 0.05$, boat versus wheeled RE, and $t=3.19$, $p \leq 0.01$,boat versus stationary ergometer). These differences suggest that further investigation of exchange of energy in rowing may be worthwhile. (No attempt may be made to use the data from this study to predict the mechanical energy savings of other scullers because of the small sample size in the study and because of the vast differences between the abilities of the experienced and inexperienced subjects.) Identification of the sources of energy exchange among segments (including the racing shell) may be a method for attempting to manipulate rowing techniques to maximize both exchange of mechanical energy and the average velocity of the racing shell.

The possibility of the presence of exchanges of energy between the subject and the shell is reinforced by the patterns of the curves for the subject and boat in Figure 3. Between the lowest point of the subject's E_{kt} curve (at about 1.75 s) and the catch (indicated by "CAT") at about 2.00 s, the energy of the boat fell, while that of the subject increased. The kinetic energy of the shell was expected to fall, as it was under the influence of drag from the water. The energy of the subject was not expected to increase before the catch, since the subject was still approaching the front of the slide with his oars out of the water. During the recovery phase of a stroke rowers try to minimize disturbances of the motion of a boat by reducing excess motion to a minimum. The only source from which the subject could have received energy at that point was the boat. The pattern of the E_{kt} curves between about 0.75 s and about 1.75 s (during the rapid decrease in the energy of the subject) permits speculation that further energy saving exists as exchange from subject to boat. In that entire second, during which the E_{kt} of the subject fell from its peak to its lowest point in the cycle, the E_{kt} of the boat increased almost continuously. The energy causing the boat's energy to increase must have come from the subject through his connection to the boat at the feet, since the only other source of energy change in the system was the viscous drag of the water. Clearly, the drag of the water did not add to the energy of the boat. These exchanges of energy among boat and crew have been evident for years, and are

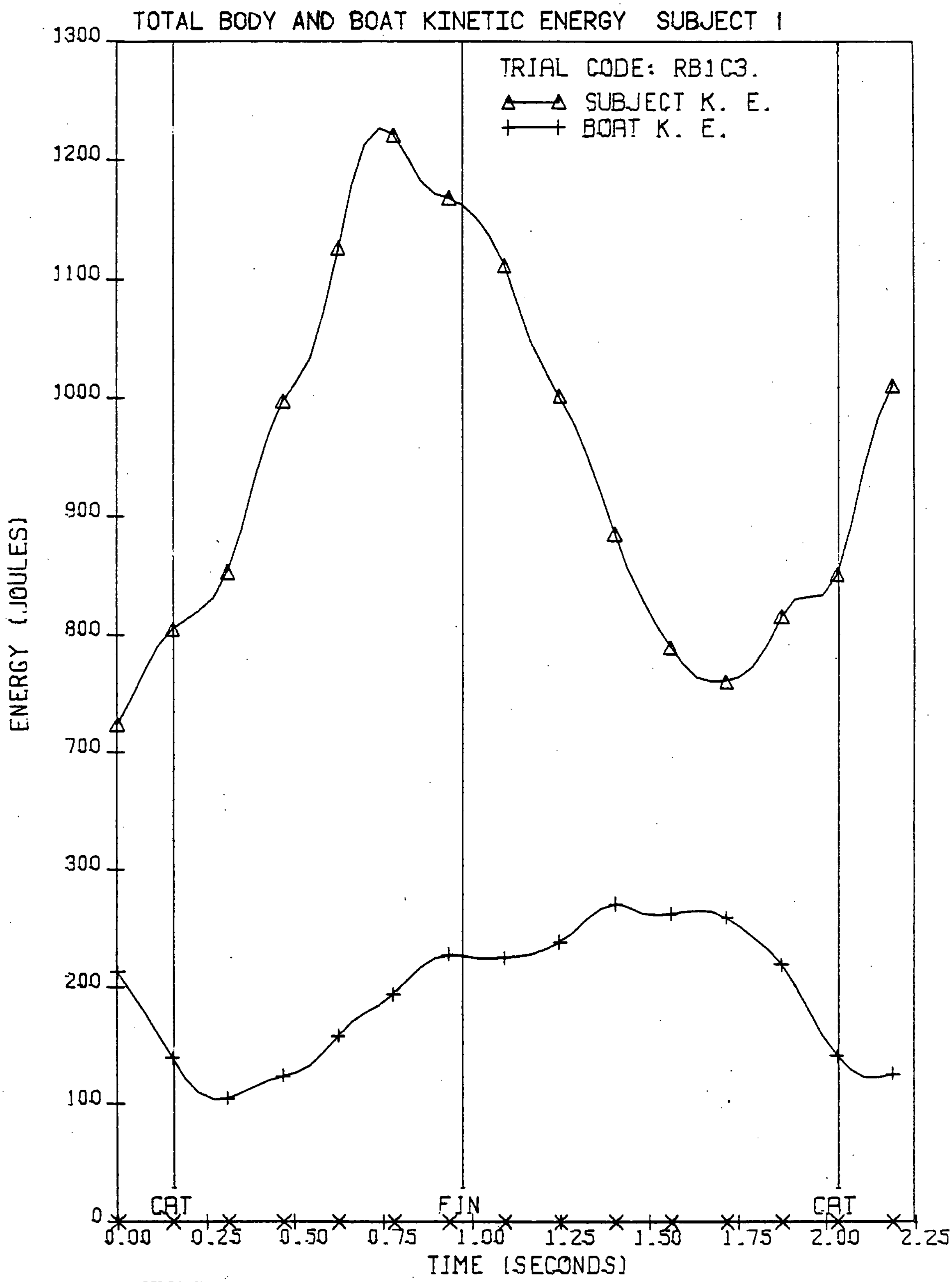

TOTAL BODY AND BOAT KINETIC ENERGY SUBJECT I
TRIAL CODE: RB1C3.
SUBJECT K. E.
BOAT K. E.
ENERGY (JOULES)
1300
1200
1100
1000
900
800
700
300
200
100
0
CAT
FIN
CAT
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
TIME (SECONDS)

FIGURE 3.

apparent in the changes of hull velocity during the stroke (e. g., Martin and Bernfield, 1980). A literature search found no previous attempts to quantify the exchanges of energy between boat and rower.

That the S_i and particularly the S_e values are higher in the wheeled RE condition allow the speculation that an oarsman would be capable of producing greater work output in a 6 min RE test on an ergometer mounted on wheels or rollers. The feasibility of such a test might be increased by tethering the RE at each end of the machine with a "damped elastic," as there is a tendency for the machine to travel "sternward" during rowing when mounted on wheels.

Average Drive Power

The powers of the drive phase (P_d of the sculling strokes, the average velocity of the shell throughout the strokes (catch-to-catch), the stroke rate, the average power of each stroke, and an estimated 2000 m race time are presented in Table 5. Powers calculated for the drive phase of some of the sculling strokes in this paper (indicated by "*") are higher than the average power estimated for maximal rowing ergometer tests of American national team candidates. Hagerman *et al.*, (1978) report average power in 310 subjects, of 360±13.8 W, with a maximal value of 407 W, calculated from the number of flywheel revolutions in 6 min maximal rowing ergometer tests. The average power required to score 5000 flywheel revolutions with the Gjessing RE used in this study is slightly greater than

400 W (1 revolution ≅ 29.4 J, time=360 s). The main difference between the powers shown in this paper and those estimated in previous rowing ergometer tests may be due to the lack of a total mechanical work measure in the ergometer tests (i. e., only the effort applied to the flywheel has been measured in the past), and to the absence of any previous estimates of the internal work and the intra-stroke work of rowing. A mechanical energy study of REs is required with a measure of the angular velocity of the RE's flywheel before correct contrasts may be drawn between the mechanical energy patterns of sculling and rowing an RE.

The methods used to estimate the average power in the shell for the entire stroke

$$(\text{average power} = (P_d \times (\text{stroke rate}))/60\ \text{s})$$

includes both the work required to move the sculler's body through the rowing stroke and the effects of the subject's efforts on the velocity of the racing shell.

Both of the estimated average powers for subject 1 sculling at 32 strokes per minute (trials RB1B2 and RB1C3) are greater than the average powers of the best oarsmen reported by Hagerman (et al)., (1978). This suggests that the average power calculated from flywheel ergometry in rowing falls short of the real power exerted in sculling. Further study of the power in rowing is necessary and should include measurement of the forces applied either at the oarlock, the oar, or the footboards, as well as simultaneous filming for a power analysis. Another suggestion is that further investigation of the mechanical energies in rowing a Gjessing RE is warranted, using a measure of the instantaneous work applied to the flywheel of the RE, as well as the internal work due to the subjects' segmental energies.

CONCLUSIONS

The data presented above support the following conclusions:

1. Based on the differences between energy savings in the boat and energy savings in the RE conditions, there exist significant differences between the movements of the sculler when sculling and those movements when rowing an ergometer.
2. The main differences in savings are due to the motion of the boat relative to the subject, which does not occur on a stationary RE.
3. The total body mechanical energy and internal work of rowing a racing shell is greater than that of rowing a rowing ergometer.
4. Since the total energy savings through exchanges and conversions in the wheeled RE are greater than those in the stationary ergometer, there is support for a proposal that future testing of oarsmen be conducted using some form of wheeled cart under the RE to permit use of higher, more race-like stroke rates in ergometer testing.

Recommendations

Based on the understanding gained with the findings of this study, the following recommendations for the study of rowing biomechanics are warranted.

1. The combination of film study and force recording in the oarlock or the oar would permit further understanding of the mechanical energy changes and power flows between the oarsman

and the boat.

2. A moving camera system, to permit larger image sizes, is necessary for the reduction of noise in the film data of rowing, if a whole stroke is to be analyzed. The Olympic rowing course in Montreal would be ideal for such a study, as several consecutive strokes could be studied, perhaps under race conditions.
3. The changes in sculling technique that may occur with fatigue during a race might be examined by filming strokes at the start and at each 250 or 500 m through the race.
4. An instantaneous measure of the flywheel angular velocity of any rowing ergometer must be included in any future study of the mechanical energy and internal work of rowing ergometers.

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APPENDIX 1 - DEFINITIONS

Rowing Terms. The following rowing terms were operationally defined for discussion of rowing actions:

catch - normally that part of the rowing stroke in which the rower puts the blade portion of the oar(s) into the water to begin pulling to propel the boat; for this study the "catch" was the position of the rower when he or she was no longer moving forward on the slide during recovery, and had not yet started to move back on the slide in the drive (this position was identified by the position of the oar handle when it was at its furthest point from the rower's body, and was neither moving forward nor backward with respect to the rower.

drive - that part of the rowing stroke in which the rower was pulling the oar handle with the blade portion of the oar squared, and beneath the surface of the water; the drive is the part of the stroke used to propel the boat.

finish - normally that part of the rowing stroke in which the rower completes the drive, stops pulling the oar handle(s), removes the blade(s) from the water, and feathers the blade(s) to begin the recovery; for this study finish meant the position of the subject when the oar handle had stopped moving backwards (toward the bow of the boat) at the end of the drive, and had not started moving forward with respect to the rower during the recovery - the opposite end of the stroke from the catch position.

rate - or - stroke rate - the stroke frequency expressed in strokes per minute, eg., "rowing at 30", "30 strokes per minute", and "striking 30," and other similar expressions are considered equivalent.

rate watch - a calibrated stopwatch which displays the stroke rate extrapolated from the time required to complete 3 or 4 strokes (depending upon the calibration of the watch face).

recovery - that part of the rowing stroke following the finish and before the catch, when the rower prepares for the next stroke.

sculling - rowing in a boat using two oars (sculls) per person, one on each side of the boat (c.f. "sweep").

shell - a boat used for flat water race rowing - also called a "skiff".

slide - the the tracks which guide the movement of the wheels of the rower's seat in a shell.

stretcher - the part of the shell used to position the rower's feet during rowing; also called "footboard"

sweep - rowing in a boat using one oar (sweep) on one side of the shell; sweeps require a minimum of two rowers while sculling may be done alone or with partners.

<u>Energy Analysis Terms.</u> Discussion of mechanical energy in this study required the operational definition of the following terms:

conversion - see "interconversion", below.

interconversion - (energy interconversion) the change in the expression of the mechanical energy within a body segment i. e., when an object is dropped from a height potential energy is converted or interconverted to kinetic energy.

exchange - (energy exchange) the transmission of mechanical energy from one body part to another e. g., energy "generated" in the anterior deltoid muscle by chemical reactions between actin, myosin, and adenosine triphosphate is transferred to the forearm segment in the action of shoulder flexion (described in Elftman (1939), Winter and Robertson (1978), and in Robertson and Winter (1980). Energy is exchanged among segments when the deceleration of one segment causes acceleration of an adjacent or nearby segment.

These definitions of interconversion and exchange of mechanical energy differ from those previously used. Caldwell (1980) used exchange to discuss both conversion and exchange. Pierrynowski, et al. (1980) used transfer to express the two values. The use of two terms whose dictionary definitions are more suited to the description of different effects of motion on the mechanical energy of an object is perhaps less ambiguous than using the same term, whether exchange or transfer, to discuss different sources of energy saving. This may be particularly important for people less familiar with the concepts and terminology of this study and others like it.

work - used to describe the change in the total mechanical energy of a segment or of a body; also called pseudowork or internal work; the energy change required to move body parts in space - distinct from external work, which is the energy change required to effect a change in the immediate surroundings of the body against gravity.

APPENDIX 2 - SYMBOLS USED IN THE PAPER

E_k - kinetic energy

E_{kt} - translational kinetic energy

E_{kr} - rotational kinetic energy

E_p - potential energy

P_d - average power in the drive phase of a stroke

S_e - energy "saved" by exchange among segments expressed as a percentage of the total mechanical work required with neither exchange nor conversion of mechanical energy.

S_i - energy "saved" by interconversion within segments, expressed as a percentage of the total mechanical work required with neither exchange nor conversion of mechanical energy.

W_e - work required to move the segments of the body if exchange of energy was permitted, but interconversion of energy was not permitted. (Equation #5)

W_i - work required to move the segments of the body allowing both exchange and interconversion of mechanical energy (Equation #4)

W_n - Work required to move the segments of the body if neither exchange nor interconversion of energy was permitted (Equation #6).

APPENDIX 3 - ENERGY PLOTS OF SUBJECTS 2, 3, AND 4

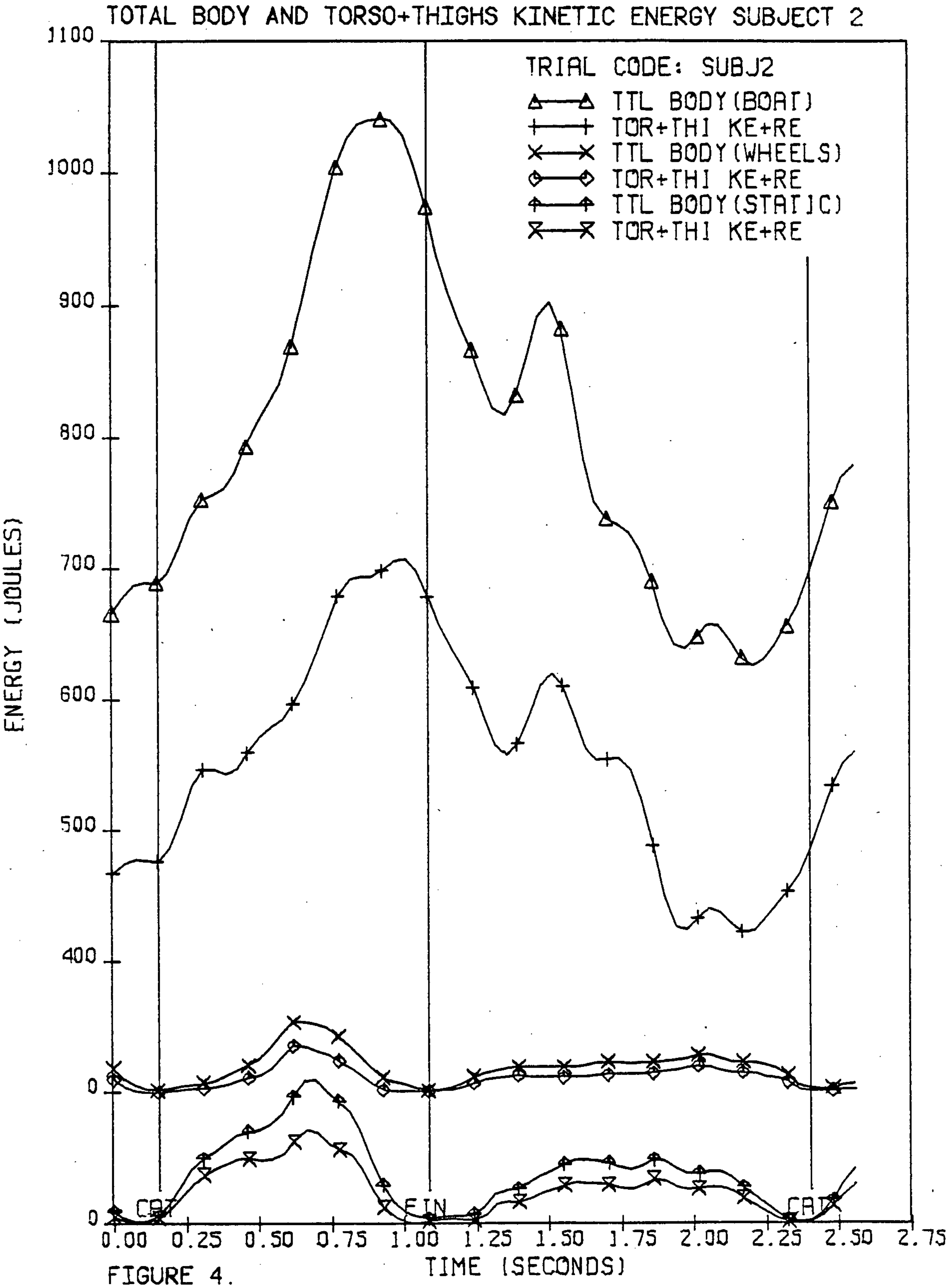
TOTAL BODY AND TORSO+THIGHS KINETIC ENERGY SUBJECT 2
TRIAL CODE: SUBJ2
TTL BODY(BOAT)
TOR+THI KE+RE
TTL BODY(WHEELS)
TOR+THI KE+RE
TTL BODY(STATIC)
TOR+THI KE+RE
ENERGY (JOULES)
1100
1000
900
800
700
600
500
400
0
0
CAT
FIN
CAT
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
TIME (SECONDS)

FIGURE 4.

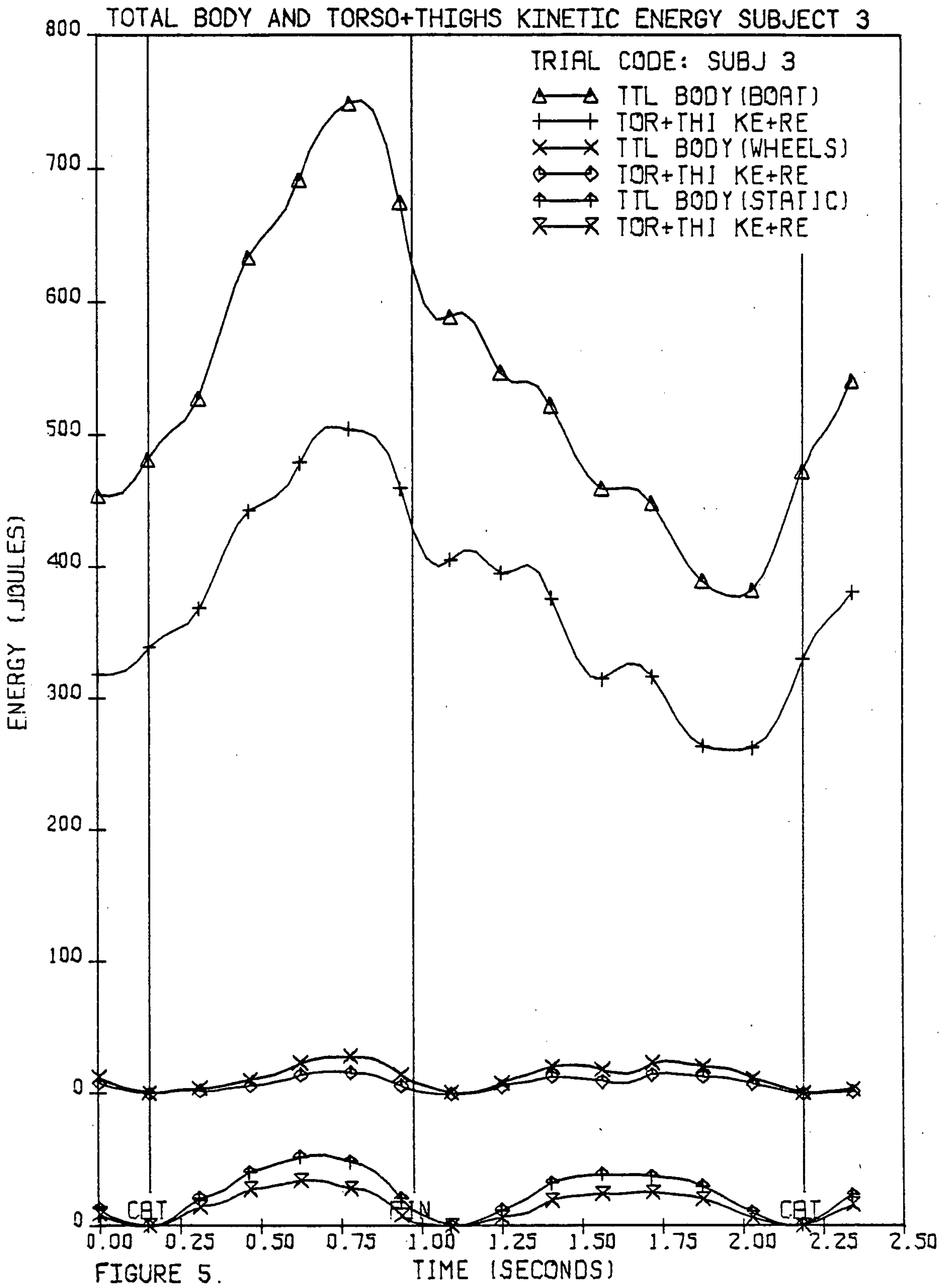
TOTAL BODY AND TORSO+THIGHS KINETIC ENERGY SUBJECT 3
TRIAL CODE: SUBJ 3
TTL BODY(BOAT)
TOR+THI KE+RE
TTL BODY(WHEELS)
TOR+THI KE+RE
TTL BODY(STATIC)
TOR+THI KE+RE
ENERGY (JOULES)
800
700
600
500
400
300
200
100
0
0
CAT
FIN
CAT
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
TIME (SECONDS)

FIGURE 5.

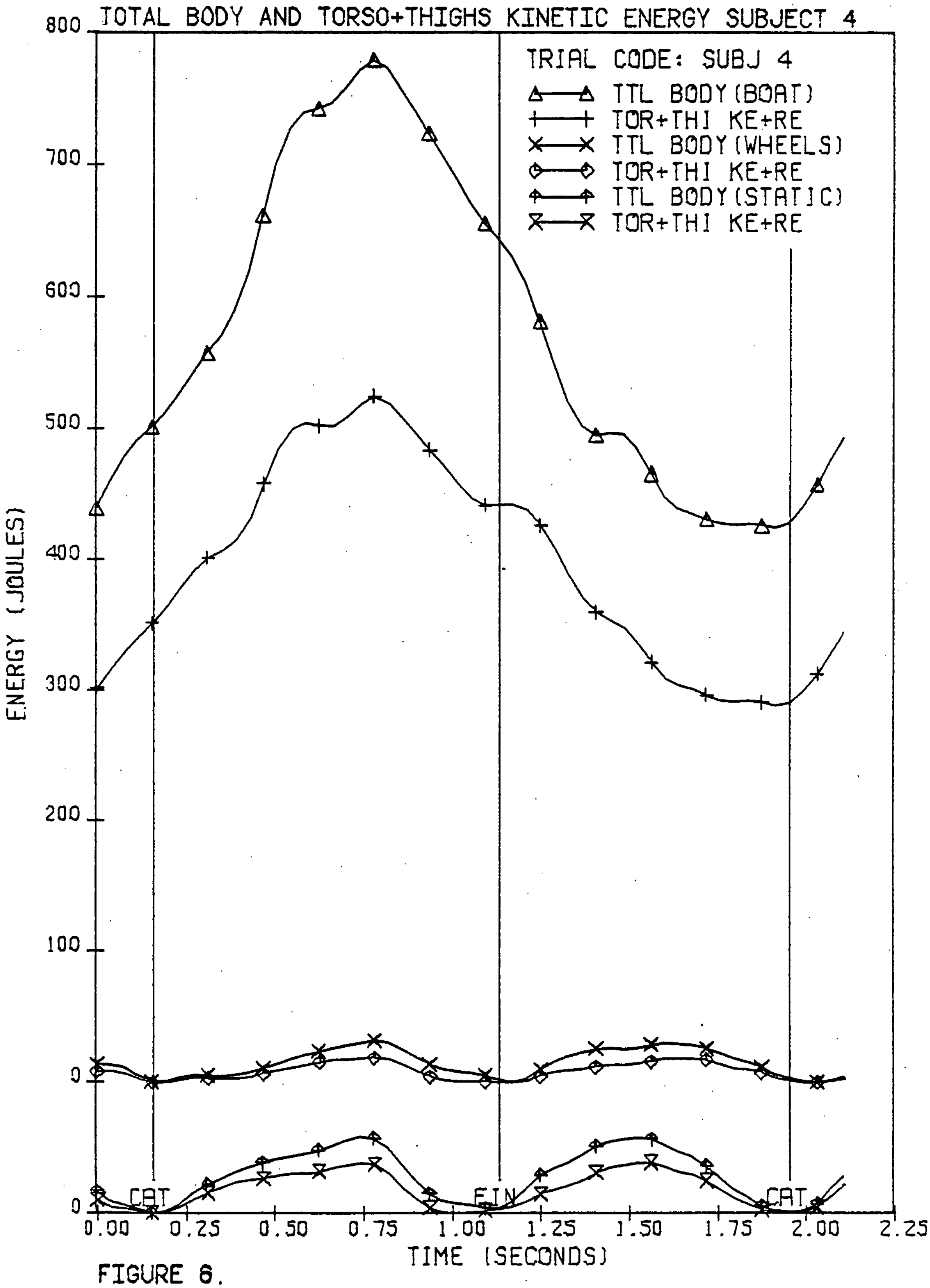
TOTAL BODY AND TORSO+THIGHS KINETIC ENERGY SUBJECT 4
TRIAL CODE: SUBJ 4
TTL BODY(BOAT)
TOR+THI KE+RE
TTL BODY(WHEELS)
TOR+THI KE+RE
TTL BODY(STATIC)
TOR+THI KE+RE
ENERGY (JOULES)
800
700
600
500
400
300
200
100
0
0
CAT
FIN
CAT
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
TIME (SECONDS)

FIGURE 6.

APPENDIX 4 - REVIEW OF LITERATURE

The study of the mechanical energy variations of rowing requires familiarity with three areas in the literature: anthropometry as applied to human movement, mechanical energy studies of human movement, and mechanical aspects of the rowing stroke. This review contains a brief survey some commonly used anthropometry studies and a short review of some recent studies of the inertial properties of human body segments. As well, an effort has been made to survey the development of the mechanical energy methods used in this study, with the aim of following the development of these methods rather than listing every paper reporting use of these methods. The section on the mechanics of rowing is incomplete, as most of the reports published on mechanical aspects of rowing are more subjective than scientific. The aim in the rowing section of this review was to be as complete as possible in surveying the English language material using objective measures of mechanical aspects of rowing.

Anthropometry

The study of the mechanical properties of human movement requires a knowledge of or a model describing the mass distribution and inertial properties of the body and its segments. There have been relatively few studies of the inertial properties of the human body, mainly because of the complexity of such studies and the difficulty in obtaining good sample distributions representative of the human population (Chandler, et al. 1975; McConville, et al. 1980).

The centre of gravity (CG) is measured in a number of ways, including reaction boards, balance boards, and "gravity lines" (i. e., locating the c.g. at the intersection of vertical lines drawn down from 3 or more different points of suspension). Moments of inertia can be measured in a few segments in live subjects by holding the segment against a maximal contraction, releasing the segment suddenly, measuring the acceleration of the segment immediately after release, and using the appropriate computation. The usual method for whole body and cadaver segment study is that of the compound pendulum, which involves "suspending the body [or segment] from some fixed point [which may be external to the object], setting it in motion by shifting it a few degrees from its equilibrium position, and determining its period of oscillation..." (Hay, 1974). This period is then entered in the equation:

$$I_o = WhT^2/4(\pi)^2$$

where -

(I_o is the moment of inertia of the body or part about an axis through the point of suspension O, W is the weight of the body or part, h is the distance from O to the CG of the object, and T is the period of oscillation.

Two other values, the moment of inertia about the CG (I_{cg}) and the radius of gyration (k) may be calculated using:

$$I_{cg} = I_o - mh^2, \text{ and}$$

$$k_o = \text{sqrt}(I_o/m)$$

where m is the mass of the object.

Braune and Fischer (1889) and Fischer (1906) present early studies of the CG and of the moments of inertia, respectively, of human cadavers and cadaver segments. These German language papers have been summarized and abridged by Krogman and Johnston (1963) and reviewed by Hay (1973,1974). The Braune and Fischer data and the Fischer data have been used in a number of early biomechanics studies e. g., Fenn (1930) and Elftman (1939).

Use of the Braune and Fischer (1889) and the Fischer (1906) data for studying the kinetic properties of human motion (particularly in athletes) is not recommended for a number of reasons. First, the cadavers used by Braune and Fischer were generally small in stature, while the one cadaver used by Fischer in 1906 was very small (44.057 kg, and 150.5 cm) (Krogman and Johnston, 1963). Second, the cadavers used in the earlier study were not positioned accurately; the saw cuts used to segment the subjects were thus inaccurate due to the inconsistent positioning of the cadavers (Hay, 1973).

The next major study of the mass distribution and inertial properties of humans is that of Dempster (1955). That paper has also been condensed by Krogman and Johnston (1963), and reviewed by Hay (1973,1974). Dempster's study included the CG of the body and its segments, the ratios of distance between the CG and each segment's ends, the mass fractions of the segments (segment mass / total body mass), and moments of inertia and radii of gyration of each segment studied. Dempster's seven cadavers were smaller, lighter, and older (the youngest listed cadaver age was 52) than the average white male or military personnel

(Dempster, 1955). Dempster's data have been used to replace that of Braune and Fischer, but are still not representative of the population of athletes from which the sample in this study was drawn.

Hay (1974) suggests that data for the cadaver in Dempster's tables of data most nearly matched with each subject be used for kinetics studies, rather than average data. More recent studies in this area have studied the inertial properties of humans with the aim of providing reliable and valid regression equations for the estimation of individual subject information. Future research in the kinematics and kinetics of humans should attempt to use this new information to describe the inertial properties of individual subjects.

Several studies have been completed of the mass distribution and the inertial properties of the human body since Dempster's. Most worthy of note are those of Clauser, et al. (1969), Chandler, et al. (1975), and McConville, et al. (1980). Clauser, et al, (1969) studied the location of the CG in 13 embalmed cadavers, in two separate planes (in most segments). The position of the segmental CGs were given as proportions of the distance between segment ends, and between certain anterior and posterior landmarks. Data from that study were quite similar to those of Dempster's (1955). The main difference between Clauser, et al., (1976) and Dempster was in the mass fractions represented by the head segment and by the torso segments. These differences are probably due to Clauser et al. having used a higher position on the neck to separate the two segments than did Dempster.

Chandler, _et al_. (1975), provide a three-dimensional study of the inertial properties of six frozen embalmed male cadavers. The small sample size, and the use of two groups of three cadavers in different positions reduced the accuracy of the proposed model. Chandler _et al_. state, almost categorically, that the data and regression equations presented are not reflections of the population of adult males, and should not be used as such.

McConville, _et al_. (1980) studied 31 living males using stereometric photography to assess total body and segmental moments of inertia in three axes. The compound pendulum method was used as criterion to assess the accuracy of the stereometric measure for total body moments. (According to those authors, if the pendulum method and the photographic method had not agreed in a trial subject, the study may not have been completed.) This appears to be the first study using anatomical landmarks to define the principal axes for the moment of inertia, rather than using some principal axis system external to the segment being studied. In all segments except the head and the neck, the regression equations developed to predict the moments about the principal x-, y-, and z-axes were significantly more accurate than the mean values, as indicated by reduced standard errors of estimate compared with the standard deviations of the moments' means. The main fault with this study was that the origin of the principal axes was located at the segmental centres of volume, usually found distal to the centre of mass, while the mass centre is the usual position about which inertial properties are studied (McConville, _et al_., 1980).

Energy and Work

Early reports describing mechanical energy in human motion are those of Fenn (1930), and Elftman (1939). Fenn used high-speed filming to study the changes in the kinetic energy of the body and its segments in sprinting. The subjects' bodies were used as reference points for the segmental motions to simplify the calculation of changes in the KE of the arms and legs, and to try to eliminate calculation of energy exchanges from body to limbs or from limbs to body. The calculated work value was extremely high since no allowance was made for transfers or exchanges of energy.

Cavagna, et al. (1964) studied running, recording from a tri-axial accelerometer placed near the CG. Accelerations were integrated with respect to time to obtain the velocity of the CG. Velocity data were then used in calculating the kinetic energy of the trunk. Cavagna et al. (1964) also studied the energies of the limbs with the trunk as a reference "point". Flaws in the use of trunk acceleration data to derive total body energy patterns (e. g., Cavagna, et al., (1964); Gage, (1964); Gersten, et al., (1969)) are discussed later in this review (Winter, 1979). Other studies have used force plates to study the velocity as derived from forces (hence accelerations) to calculate KE (eg., Cavagna and Margaria (1966), Cavagna, et al., (1971,1976)). The problems associated with this approach are similar to those associated with using the acceleration of the CG for energy assessment. Both the Fenn (1930) and the Cavagna (1964) reports estimate the KE of the limbs incorrectly. Smith

(1975) indicates that Fenn's calculations apply only when the segmental velocity is perpendicular to that of the body, a rare occurrence, and that absolute segmental velocity (both vertical and horizontal components, in a two dimensional study) must be used to calculate the KE of a limb or segment.

In a classic study of the kinetics and kinematics of walking, Elftman (1939) synchronized force-plate data with film data to examine the rates of transfer of mechanical energy among segments. Energy exchange was not studied. Replication of Elftman's study is difficult, because there is no indication of the formulae used to compute the energy-time patterns. The chief hindrance to Elftman was the need to use manual techniques to differentiate displacemant data to obtain segment velocity and acceleration information from the film. These manual techniques also affected the accuracy of Fenn's study.

Introduction of computer technology to gait studies has greatly increased the quantity, and, it is hoped the quality, of data that can be studied. Errors associated with manual data collection have also been reduced, by reducing the opportunity for humans to collect data. The chief remaining source of human error is now at the stage of film data collection (Winter, et al. (1974), Pezzack, et al. (1977)). Quanbury, Winter, and Reimer (1975) studied the mechanical energy patterns in walking, using a television-computer interface to collect raw kinematic data automatically. Joint forces and power flows were computed for all segments, starting with the swinging leg, and working back through the pelvis to the supporting leg. These calculations were done only for the single leg support phase of the walking stride. An estimate of ground reaction force (GRF) to the supporting foot was computed. It may be theoretically possible to calculate GRF from kinematic data, but the human body is not ideally suited to the analysis, as it violates the assumptions of the link-segment model in a number of ways. Quanbury, et al. (1975) were unable to corroborate their calculated GRF with real force plate data.

Smith (1975) contrasted the use of absolute velocity and the rotational velocity of segments with Fenn's (1930) method of calculating KE, in studying a jumping movement. It was shown that Fenn's method (also used by Cavagna, et al. (1964)) was insensitive to a significant amount of the KE present in most human movements, as it was only valid at the very rare instance when a segment's velocity was perpendicular to the body's velocity. Norman, et al. (1976) coined the term "mechanical pseudowork" to describe the changes in mechanical energy of the limbs and segments during walking. Pseudowork was computed as the sum of the absolute values of all potential and kinetic energy changes, for all segments in a link-segment model, for all of the time intervals (film frames) included in the movement. This "pseudowork" is equivalent to the term "W_n" (equation #6), used in the present study. Using the absolute values of all intra-segment energy changes, as in Wn, creates an artificially high "work" term.

Winter, (1979) expanding on the concept of pseudowork, defines "internal" work of human movement as all potential and kinetic energy changes that occur in all segments of the body during movement. The distinction drawn between internal and external work is that external work is a measure of movement of an object (the body) through some vertical displacement i. e., a change in PE or an increase in velocity; internal work is a measure of the energy changes (PE and KE) occuring in all segments while moving, perhaps during external work. Internal work is the sum of the total mechanical energies of all segments, in all time intervals of a movement. This calculation differs from pseudowork (Norman, et al. (1976) in that internal work is the "raw" sum of the energy changes, while pseudowork is the sum of the absolute values of those energy changes. The triangle inequality ($|a+b| \leq |a|+|b|$) dictates that internal work is always less than or (rarely) equal to pseudowork. Winter's (1979) term "internal work" is equivalent to the W_i computed earlier in this paper (equation #4). A minor problem in the calculations presented by Winter is that, although the external work is assumed to equal zero the digitizing process usually introduces some small amount of external work. This occurs when the total body energy at the end of a movement cycle is different from that at the beginning of the cycle. Often, in controlled situations, the error is due to small errors (noise) in the digitized data, introduced by the human operating the digitizer. This error was recognized and corrected for by Pierrynowski, et al. (1980).

Winter's internal work term is credited with identifying changes in the mechanical energy of the body and segments which are not detected by studying the motion of the total body CG. Movement of the limbs in reciprocal movements such as walking and running requires some work from the muscles, along with passive energy changes. Motions of the limbs are not detected by following the CG, as in Cavagna, et al. (1964). Winter (1979) compared the energy patterns of the CG with the internal work (W_i) of the body, and showed that the CG "work" underestimated the actual mechanical work of walking (measured with the method for W_i, this paper) by 16 to 40 percent.

Pierrynowski, Winter, and Norman (1980) further adapted the calculations of the energy analysis. The "work" calculation was further partitioned to permit (mathematically) the exchange of energy within segments, but not the transfer of energy among segments. This was done by adding the absolute values of the "instantaneous" changes of the segment total energies. The equivalent calculation is that of "W_e" (equation #5, this paper). Pierrynowski, et al. (1980) then removed apparent external work (W_t, equation #3, this paper), and calculated energy transfers and exchanges by subtraction of the appropriate "work" terms.

Pierrynowski, et al., (1980) also calculated an efficiency term, attempting to account for internal work, external work, and the different efficiencies of concentric and eccentric muscular contraction. The choice of the numbers used to represent the metabolic efficiencies of the different contractions appears to have been somewhat arbitrary, however, and is open to question.

Robertson and Winter (1980) studied joint and muscle powers, and segmental energy patterns of the lower limb in normal walking. The link-segment model and finite difference arithmetic were used to derive instantaneous mechanical energy from film data. A force plate was used in conjunction with the film data to study the joint powers. Total power and segmental energy curves were very similar for the entire stride in the thigh and shank segments, and for most of the stride in the foot. The foot segment energies showed little change through the entire step cycle, while the ankle joint powers varied considerably at the weight acceptance and push-off stages of the step. This difference between power and energy results for the foot was attributed to the large joint power and muscle power components (opposite in sign), where a small error in measurement would cause considerable change in the total power delivered to the foot.

Pierrynowski, Norman and Winter, (1981) applied the energy calculations to the study of load carriage on a treadmill. One of the conclusions of that study was that the methods previously used to study normal and pathological walking could be applied to the study of load carriage and possibly to study of backpack design. Another study using these methods for other forms of locomotion is that of Caldwell (1980). Caldwell studied the mechanical cost and the energy transfers (and exchanges) in two levels of cross-country skiers . More skilled (internationally competitive) ski racers were found to exchange and transfer a greater proportion of the total "pseudowork" than novices. Problems associated with stationary cameras outside of the laboratory were identified as:

- camera-object distance has to be large,

- a wide field of view is needed to ensure filming

at least one complete movement cycle,

- the two restrictions above combine to give very

small image size, thus a low signal:noise ratio;

In the present study the accuracy of the digitizing was restricted as the projected (digitized) image was only about 3% life size.

Komi, et al., (1981) studied the mechanical energy of nine runners at the speeds at which blood lactate begins to accumulate. High correlations were found between the average power output at the measured velocities and the percentage of slow-twitch muscle fibres measured from biopsies of the vastus lateralis muscle. Subjects were not tested, nor were mechanical energies assessed at running speeds other than the lactate "threshold". Future running studies with metabolic and energy measures should test at a variety of speeds in each subject, to test for further relationships between the mechanical and metabolic features of running.

Mechanics and Rowing

Few English-language studies exist in the mechanical aspects of rowing. A search of the literature found no studies using the mechanical energy approach to study the rowing stroke cycle. Most existing literature on the mechanics or biomechanics of rowing consider hydrodynamics, boat and equipment design force at the oar-handle (and consequently, at the blade), or the effects of stroke rate on shell velocity. Most other literature (not reported here) contains relatively subjective observations of the kinematics of rowing.

A recently published review of physiological and biomechanical aspects of rowing and paddling sports is useful as it discusses some of the non English-language papers on rowing (Zsidegh, 1981). The effect of stroke rate upon impulse (in each stroke and over a timed interval), and studies on stroke technique, force development, and rigging are mentioned. Zsidegh's review is useful for guiding a search of the non-English work on the mechanics of rowing.

Williams (1967) describes the "ideal" motions required of the oarsman in taking a stroke, and discusses the timing of the power application in a rowing style not common in modern rowing. Cameron (1967) evaluated shell design, oar stiffness, and other structural aspects of rowing equipment; little attention was paid to actually using the equipment. Wellicome (1967) evaluated the various effects of water depth, boat breadth (widest point) and length, oar design, shell cross-section, surface roughness, viscous drag, and wave dynamics on the relative velocity of a rowing shell.

Pope (1973) designed a theoretical model to include force at the oar, power application with respect to the position of the oarlock, and other factors. The model simplified the effects of asymmetric force application (causing yaw), and of the movement of the system's total CG during the stroke. Some insights were gained regarding the potential effectiveness of changes in the position of the oarlock relative to the position of the front of the slide. Pope appears to recognize numerous human factors exerting at least as much influence on boat speed as the equipment. After developing the model at length, Pope states, "... rowing is an affair of men, and this must be clearly understood."

McMahon (1971) studied the effect of boat design on the racing speeds of lightweight and heavyweight crews. A theoretical lightweight shell was modelled to be geometrically similar to a heavyweight shell, in terms of the ratios of crew weight to the length, breadth, and wetted surface area of the shell. It was proposed that similar shells rowed by lightweight and heavyweight crews should finish a race in the same time.

Another approach to mechanics in rowing is that of Brearley (1977). The moment about the stern of eight-man racing shells was calculated for "standard" rig and for an alternate rig of the oars. The standard rig, with the sweeps staggered from bow to stern, with bow (#1) on starboard and stroke (#8) on the port or left side of the shell), was shown to cause the boat to waver in its course throughout each stroke. This wavering is due to the difference between the sum of the distances from the stern to the riggers on protside and the same sum on starboard. At different parts of the stroke, the greater sum of distances of the starboard riggers causes the bow of the boat to be pushed or pulled slightly off course at the catch and finish, respectively. The alternate rig, with bow, 3, 5, and stroke (#8) on the same side, and 2, 4, 5, and 7 on the opposite side eliminates the moment about the stern, as the sums of the distances from the stern to the riggers are the same for both sides of the boat.

Ishiko (1971) measured the force at the oar with strain guages on the inboard portion (between the end of the handle and the oarlock) of an oar, and the acceleration of the shell. Force curves were found to vary greatly from subject to subject even among elite members of the same crew. The accelerations of the boat were related to the force-time patterns of the oar, but neither force nor acceleration were adequately related to the kinematics of the subject's motions.

Asami, et al. (1978), and Schneider, et al. (1978) report force-time curves for oars or oarlocks, determined with strain gauges. Force-time curves were generated in rowing by a number of oarsmen with different skill levels. The force-time curves were considered as possible instructional information to assist in teaching oarsmen improved technique, and to identify skilled performance. The chief difficulty with these data is that the telemetry equipment needed to collect force information at the oarlock or oar shaft is prohibitively expensive.

Celentano, et al. (1974) studied the forces in the oar during rowing at stroke rates between about 20 and about 37 strokes per minute. The effects of stroke rate of the velocity of a pair without coxwain, on stroke (and drive phase) duration, and total "work" done per stroke were also studied. The shell's fluctuation about its mean velocity was found to be reduced at stroke rates greater than 35 per minute. The power output, force, and the proportion of the stroke taken by the drive phase were found to increase with rate.

Martin and Bernfield (1980) studied film data to measure the velocity of an eight with coxwain at three stroke rates between 37 and 41 strokes per minute. The least fluctuation in velocity (a range of 2.65 m/s) occured at 39 strokes per minute. The greatest mean velocity was 6.41 m/s, and occurred at 41 strokes per minute. These results extended the findings of Celentano, et al. (1974). The chief contributions to the increased velocity of the shell at higher rates were greater force per stroke, and the increased percentage of the total stroke cycle time spent exerting the force (i. e., increased impulse).

Studies mentioned above as investigations of the forces occurring in the oar or in the oarlock (measured at the pin) appear to make no mention of the difficulty and expense involved in taking these measures. In a description of a computerized data system for a four-oared shell, Klavora (1979) describes several problems experienced by, for example, Ishiko (1971), and by several other coaches and researchers. A system described by Klavora was described as having an "attractive" price, far greater than any funding available for this study (i. e., the 1979 price was estimated at about $10,000)

A study of the position of the oarsman at the catch, and the effect of that position of the force developed in the drive phase of the stroke showed little, except that: unless subjects are very highly skilled they are likely to be unable to duplicate a skilled motion reliably and, the environment for testing rowing motions must be made as similar to the real rowing motion as possible (Klavora, 1978).

Very few studies have been published describing comparisons of the mechanics of rowing with ergometers and rowing in shells. Stuble, Erdman, and Stoner (1980) studied the kinematics of rowing in a boat and rowing two different types of rowing ergometer. Eight subjects were filmed through several strokes in coxless pairs and in the two machines, and the kinematics of the hands and of several relative angles (e.g., thigh-trunk angle) were examined graphically. Stuble, et al. were able to discern between members of different rowing clubs and between skill levels. The movement out of the saggital plane occurring in sweep-oar rowing was ignored, and only motion in the x-y (vertical-anteroposterior) plane was examined, as in this investigation.

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