An On-Water Analysis System for Quantifying Stroke Force Characteristics During Kayak Events

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A system was developed to quantify the on-water forces, impulse, and power generated by a kayak paddler. The system is lightweight (<1 kg), portable (i.e., it can be used in single [K1], double [K2], and fours [K4] boats), and does not affect the integrity of either the kayak paddle or the boat. Changes in the strain on the kayak paddle were measured by force transducers attached to the shaft of the paddle, and these signals were then recorded on an FM tape recorder located in the boat. The data were then analyzed by the Kayak Data Acquisition and Analysis System software which graphically presented the paddlers' force time curve as well as a printed tabular report on the paddlers' average force, impulse, work, power, and the instantaneous boat velocity.

Scientific analysis of kayakers has generally focused on physiological testing of the athletes to determine fitness levels and to then tailor training programs to optimize physiological fitness. However, peak physical fitness alone does not guarantee success at an elite level; indeed poor technique can decrease a paddler's physiological efficiency by increasing the amount of internal extraneous work done by the body. At elite levels, this decrease in efficiency due to biomechanical factors can be the difference between winning and losing. Therefore an understanding and optimizing of the biomechanical characteristics of the kayak stroke should be of concern to both elite kayakers and their coaches.

Several researchers have analyzed the kayak stroke using cinematographical techniques (Dal Monte & Leonardi, 1976; Mann & Kearney, 1980; Plagenhoef, 1980). However, because both upper limbs and the paddle form a closed loop kinematic chain, it is difficult to calculate the forces applied to the paddle using cine analysis.

Vos, Kimmich, Makinen, Ijsenbrandt, and Vrijens (1974) measured the average force that a paddler applies to the paddle under four conditions, namely, average training pace, start pace, pace for 500-meter competition, and sprint pace. They attached strain gauges to the shaft of the paddle and measured the force applied to the shaft. The data were transmitted via telemetry to a land based

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computer. The primary aim of their research, however, was not to study the forces applied to a kayak paddle but rather to demonstrate the uses of telemetry in measuring dynamic forces in endurance sports.

Systems have also been designed for measuring forces developed by rowers. Ishiko (1971), Ishiko, Katamoto, and Maeshima (1981), and Schneider, Angst, and Brandt (1977) attached strain gauges to oars and measured the force on the blade; then, using telemetry, they sent the signals received via an FM transmitter to a shore based recorder. Smith, Spinks, and Moncrieff (1988) measured the forces developed by a rower by determining the strain produced in the oar with a linear proximity transducer.

The size and weight of a linear proximity transducer precludes it from being a viable option for use in the present study. The other alternative therefore is to use strain gauges in a Wheatstone bridge configuration.

The purpose of this project was to develop an accurate, portable, and lightweight computerized system for determining the on-water forces generated by a kayak paddler. Data gathered using such a system will give the coach an objective basis for prescribing technique modifications aimed at enhancing performance. In addition, the system has the potential to evaluate the hydrodynamic properties of different paddles and eventually could be modified to provide instantaneous feedback about the paddler's stroke.

**Method**

**Design Requirements**

In the design stages of our kayak data acquisition and analysis system (KDAAS), we ensured that each component of the acquisition system would meet some fundamental requirements. First, the data acquisition system must be portable so that it can be used in different boats (i.e., single [K1], double [K2], and fours [K4]). Second, this system must be waterproof since it will be used on the water; therefore any water splashed onto the system must not affect its performance. Third, it must be lightweight. It should not significantly increase (<3%, or approximately 2–3 kg) the normal combined weight of boat and paddler.

The instrumentation on the paddle must not interfere with the paddler's normal technique. Furthermore, the characteristics of the paddle (i.e., weight, length, blade pitch, blade surface, and balance) should not be altered, and the force transducers that are chosen must be stable across changing ambient humidity and temperature conditions. The data recorder must be able to collect signals for at least 5 minutes (the approximate time for a 1,000-m race) and obtain simultaneous records from four different paddles to accommodate analysis of a K4 boat.

**Hardware Instrumentation**

*Strain Gauges.* Four aluminum foil strain gauges (Kyowa type KFC-10-C1-11) were attached to each end of the paddle shaft (1 cm and 5 cm proximal to the insertion of the blade onto the shaft) to measure the bending of the shaft (Figure 1). This location allowed the gauges to be between the force being applied at the hand position and the reaction force at the blade of the paddle. The strain gauges were arranged to form a full Wheatstone bridge (Figure 1a), with the
Figure 1 — Diagram showing location of strain gauges on the paddle and schematic model of force determination via resistive change in the Wheatstone bridge. (a) Circuit diagram of connected gauges in Wheatstone bridge (in this configuration, Gauges 1 and 3 measure elongation and Gauges 2 and 4 measure compression).
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gauges applied 180° apart at both ends of the paddle with their sensitive axes parallel to the longitudinal axis of the paddle shaft. In this configuration the shear force applied to the paddle can be measured (Figure 1).

Strain at a point is equal to the bending moment at that point divided by a constant. Therefore the strain at point G1 (Figure 1) is proportional to the moment at that point (M1), which in turn is equal to the applied force (F) multiplied by the distance (x1) between the gauge and the applied force. Similarly, the strain at point G2 is proportional to the moment at that point (M2), which is equal to the applied force (F) multiplied by the distance (x2) between the gauge and the applied force. From the circuit diagram in Figure 1, the measured bending moment at G1 is subtracted from the measured bending moment at G2 (i.e., M2 - M1 = F(x2 - x1)), since the distance between the two gauges (i.e., x2 - x1) is a constant (d).

\[ F = \frac{M_2 - M_1}{d} \]

where F is the shear force applied to the paddle. Shear force applied to the paddle is therefore proportional to the resistive change at G2 minus the resistive change at G1.

To minimize the effects of water and temperature, the strain gauges were coated with a silastic compound that protected them but did not affect their sensitivity. Two small holes were drilled in the shaft of the paddle so that the cables connecting the strain gauges and amplifier could be internalized in the shaft of the paddle, allowing for an unencumbered paddle. In addition, the proximity of the transducers to the amplifier reduced the effects of noise and resistance on the signal. The excitation voltage for the Wheatstone bridge was supplied by two 9V batteries which also provided the power for the amplifier.

Amplifier. An eight-channel amplifier was designed and built. It provided the initial excitation of the strain gauge bridges and was also used to amplify their output signals before they were collected on the data recorder.

Velocity Meter. A velocity meter was supplied by Trius Electronics. The meter used a strain gauge element to detect a change in pressure across a sensor suspended beneath the kayak. This pressure was then mathematically equated to velocity using calibration data provided by the company.

Data Recorder. A Teac data recorder was chosen as it allowed the recording of the forces applied to four paddles as well as the boat velocity.

Hardware Calibration

Since there is considerable variation in the elasticity of different paddles, calibration of each paddle end was necessary. The paddle was calibrated using the following procedure (assume the right-hand end of the paddle is being calibrated). The left end of the paddle was positioned on a support at the normal hand position (Figure 2).

Another support was placed in the middle of the right blade to simulate the effect of the water on the blade. It was assumed that the force was acting upon the center of the blade. In earlier work, measurements had been made at both extreme ends of the blade; differences were found in the output of the strain gauges, depending on where the support was located under the blade. The
Figure 2 — Paddle calibrating jig.

differences were due to "end effects" (where the gauges are mounted relative to the end of the shaft). The effect was not considered significant since there was less than a 7% difference between the two ends of the blade. From the right-hand position ("A" in Figure 2), masses from 5 to 30 kg in 5-kg steps were suspended. This setup simulated the effect of a paddler applying a static force to the paddle during a kayak stroke. To calibrate the left end of the paddle, the same procedure was adopted but the right end of the paddle was secured in the jig.

The application of force to the paddle caused elongation and compression of the strain gauges, and this deformation caused a change in the voltage across the Wheatstone bridge. This potential was measured on a previously calibrated multimeter. By taking moments about the left-hand end of the paddle ("B" in Figure 2), the force on the blade can be determined and a conversion factor relating the change in voltage to the applied force can be calculated.

Strong linear relationships were found between the force applied to the paddle ends (0 to 300 N) and the change in resistance within the Wheatstone bridge ($r=0.99$). These linear relationships were then used as part of the calibration factors in the software. The process of calibration was repeated a number of times to ensure reliability of the gauges, and output deviation was found to be less than 5%.

Software Instrumentation

The software was written in two modules, both in Microsoft Quickbasic (ver. 4.5). The first one controls the analog-to-digital (A/D) conversion board, which extracts the data from the FM tape, records, and then stores the data in various arrays. The second module processes and displays the data to the system user.

Module 1. A Data Translation (DT2814) 12-bit A/D board was used for conversion of data since it can be fitted into either a lap-top or standard computer (i.e., it is a half height board), and its specifications met the requirements of this project (i.e., 16 analog input channels, ±5V input range and maximum sampling rate of 40 kHz).

The software performs three functions: (a) preparation of the board for
sampling (i.e., sampling rate and number of channels to be sampled); (b) activation of the board and transmission of a flag to begin sampling from the FM tape recorder; and (c) storage of the sampled data on disk. This module can be installed as a menu option of the main data analysis software or can be run as a stand-alone program.

Module 2. The software in this module was designed to be used on the minimum of an IBM-AT or compatible computer with hard disk and at least an enhanced graphics monitor (i.e., EGA card and monitor). This configuration was required because the amount of data to be collected and analyzed makes the use of an IBM-XT prohibitively slow. The enhanced graphics monitor is required because it provides a relatively high degree of resolution, which therefore allows good on-screen graphic presentation.

Software for this module performs three main functions: (a) allows the user to load the data that were saved in Module 1; (b) allows the user to enter calibration and adjustment factors to modify the data (i.e., adjust for the amplifier offset and then equate the voltage change to the applied force); and (c) displays the data in graphical presentation on the screen and provides a tabular and graphical printed output.

The software package (Kayak Data Analysis System, KDAS) consists of a single screen display that is divided into three separate view ports: two text windows and a graphics window. The user interacts with the software through five dropdown menus, with each menu providing a number of options.

The system was designed to provide measures of one, two, or four paddlers in a boat, and the following information can be determined for each paddler.

1. Forces applied to the paddle by the right and left hands as a function of time;
2. The impulse applied by the left and right hands;
3. The instantaneous velocity of the boat;
4. The total work done by the athlete during each stroke (a stroke is considered to be the cycle beginning when the right paddle makes contact with the water until the next time it makes contact);
5. The power developed per stroke by the paddler;
6. The maximum force produced for each stroke along with the time taken to reach this maximum;
7. The time the paddle is in contact with the water per stroke;
8. The difference in time between the points of initial force application by the two (or four) paddlers;
9. The difference in time between the points of maximum force application by the two (or four) paddlers;
10. The difference in time between the points of cessation of force application by the two (or four) paddlers.

Results and Discussion

To illustrate the potential of the measurement system, sample data of a subelit paddler racing over 500 m is outlined below. Mean data for peak force, impulse, and time to peak force is indicated in Table 1.
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Table 1
Results Obtained From a 500-m Training Session of Subelite Kayak Paddler (N = 25)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Left paddle</th>
<th></th>
<th>Right paddle</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SE</td>
<td>Mean</td>
<td>SE</td>
</tr>
<tr>
<td>Peak force (N)</td>
<td>200.6</td>
<td>7.9</td>
<td>213.5</td>
<td>9.6</td>
</tr>
<tr>
<td>Impulse (Ns)</td>
<td>48.7</td>
<td>0.7</td>
<td>51.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Time to peak force (ms)</td>
<td>230</td>
<td>10</td>
<td>210</td>
<td>6</td>
</tr>
<tr>
<td>Wet time of paddle (ms)</td>
<td>570</td>
<td>16</td>
<td>590</td>
<td>14</td>
</tr>
</tbody>
</table>

The data were then normalized and mean force time curves for the left and right paddles were graphed (Figures 3a and 3b). The coefficient of variation was calculated for both the left and right graphed output.

**KDAAS**

We have developed a system (KDAAS) that acquires and analyzes the force characteristics of the on-water kayak stroke. The data acquisition module consists of a strain gauge system attached to the paddle. The system is lightweight, mobile, waterproof, and does not interfere with the normal paddling stroke. The system is easily calibrated, does not affect the design of the paddle, and is stable across varying temperatures and humidities.

The software for the system is designed in two modules; the first module controls the A/D board and the second module processes and displays the data to the system user. Both modules are controlled by dropdown menus for user friendliness and can be run either simultaneously or independently.

**Limitations and System Improvements**

Although the system functions well and meets the specifications required, some further refinements could be made. The use of an FM recorder is a limitation because it is not possible to view the data in real time. To rectify this limitation, a telemetry system needs to be developed to handle nine input channels and transmit signals over a distance of at least 1,000 m. This would allow KDAAS not only to be a biomechanical testing instrument but also to serve as an invaluable coaching tool.

**Conclusion**

A system has now been developed that allows biomechanists and coaches to quantitatively analyze the technique of single and team boat kayak paddlers. The development of this system provides the groundwork for further research such as

1. The development of a data base of performance statistics for different levels and events;
2. The development of objective criteria for selection of crew members in team boats; and
3. The technique analysis for optimizing the kayaking stroke.

References

Dal Monte, A., & Leonardi, L.M. (1976). Functional evaluation of kayak paddlers from...


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