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Journal of Biomechanics 33 (2000) 241–245

JOURNAL OF BIOMECHANICS

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Technical note

# A new instrumentation system for training rowers

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Received 4 September 1998; accepted 9 July 1999

**Abstract**

A dry-land rowing system was developed to provide the coach and/or athlete with quantitative information about the athlete's kinetics and kinematics while the athlete trains. This system consists of a Concept II rowing ergometer instrumented with a force transducer and potentiometer, four electrogoniometers attached to the athlete's ankle, knee, hip, and elbow, and a data acquisition computer. The force transducer is used to quantify the athlete's pulling force. The potentiometer signal is used to locate the position of the handle. The electrogoniometers provide signals proportional to joint angles. A link segment model of the human body is used to locate joint centers based on limb lengths and joint angles. The computer is used to collect and process all the transducer signals, perform the link segment calculations and provide feedback to the coach or athlete in the form of a stick figure animation overlaid with kinematic and kinetic information. This system allows the coach and athlete to quickly study a rower's mechanics, to evaluate the effects that technique changes have on the power produced by the athlete, and to identify technique differences between athletes. © 2000 Elsevier Science Ltd. All rights reserved.

*Keywords:* Rowing; Ergometer; Feedback; Training; Instrumentation

## 1. Introduction

Competitive rowing is an extremely technical and physically demanding activity. The task of propelling a racing shell across a given distance of water as fast as possible involves the interaction between physical strength, endurance, technical skill of the athlete, and the design of the shell/oar system. A potentially valuable tool for training both novice and elite rowers is a feedback system that provides the athlete with quantitative information about his/her rowing mechanics and the instantaneous power developed throughout a stroke as he/she rows.

Though the technology is available to construct a training tool of the type described above, the literature does not suggest that such a device exists. Researchers have studied physiological aspects of rowing (Di Prampero et al., 1971; Hagerman et al., 1978; Hagerman, 1984), movement kinematics and kinetics during rowing (Bompa, 1980; Martin and Bernfield, 1980; Struble et al., 1981; Schneider and Hauser, 1981; Asami et al., 1981; Nelson and Widule, 1983; Deming et al., 1988; Hartmann et al., 1993; Roth et al., 1993; Pudlo et al., 1996; MacFarlane et al., 1997), and boat/oar loading (Celentano et al., 1974; Deming et al., 1988; Roth et al., 1993). Typically these studies involve considerable lag time between the data collection, data processing and analysis, and finally the presentation of the findings to the coach or athlete. This lag time limits the coach's effectiveness in using the information to modify technique and evaluate the impact these modifications have on performance.

The objective of this study was to construct a dry-land rowing system that provides immediate feedback about the rower's joint kinematics, pulling force and pulling power. The unique feature of this system is its ability to provide immediate feedback on both human movement characteristics and the force and power delivered to the rowing handle throughout a rowing stroke. This feature allows the coach and athlete to quickly identify movement strategies that maximize propulsive power. Further, the feedback information can be compared between rowers and used to assist coaches in team selection.

## 2. Methods

The biofeedback system (see Fig. 1) contains both hardware and software components. The hardware

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PII: S0021-9290(99)00139-6

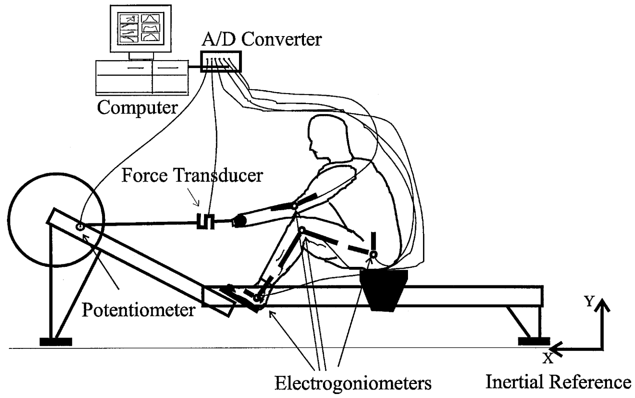


Fig. 1. Schematic diagram of the data acquisition equipment and setup used in the biofeedback rowing system. A force transducer generates a signal proportional to the athlete's pulling force. A potentiometer is used to locate the position of the rowing handle relative to the chain gear. Four electrogoniometers are used to quantify ankle, knee, hip and elbow joint angles. A data acquisition computer records and processes all signals and then displays a stick figure animation of the rowing motion overlaid with kinematic and kinetic data.

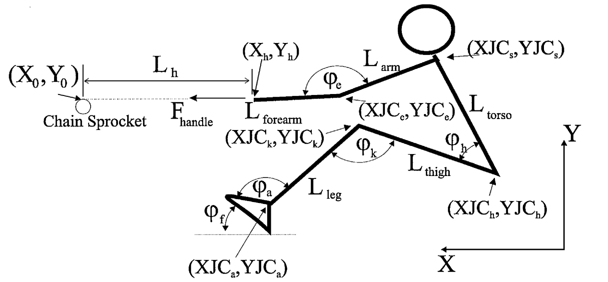


Fig. 2. An illustration of the various quantities used to calculate joint center locations, joint angles, and the pulling force. Limb lengths are recorded prior to a training session. The $x$, $y$ locations of the ankle joint center ($X_{JC_a}$, $Y_{JC_a}$) and ergometer chain gear ($X_0$, $Y_0$) are measured relative to an inertial reference having an origin on the floor behind the ergometer. The foot angle $\varphi_f$ remains constant and is determined by the angle of the ergometer footplate. Ankle, knee, hip, and elbow angles ($\varphi_a$, $\varphi_k$, $\varphi_h$, $\varphi_e$, respectively) are determined based on signals from the electrogoniometers. Joint angles and limb and torso lengths (i.e. $L_{leg}$, $L_{thigh}$, $L_{torso}$, $L_{arm}$, $L_{forearm}$) are used in a link segment model of the body to determine joint center locations.

consists of four electrogoniometers attached to the athlete, a potentiometer and force transducer attached to a commercial dry-land rowing ergometer, and a computer and custom software for collecting, processing and displaying data derived from the various instrumentation.

The electrogoniometers are used to quantify a rower's ankle, knee, hip, and elbow flexion/extension angles. The electrogoniometers have one degree of freedom and were custom designed using 1-turn potentiometers (RadioShack, Alpha 10 kΩ resistance) and aluminum and brass bars fitted with nylon straps for attachment to the limbs. Each electrogoniometer was calibrated using a manual goniometer. Joint angles are defined to be 180° in the fully extended position, decreasing with joint flexion.

A dry-land rowing ergometer (Concept II Model B) was instrumented with a force transducer (Omega Engineering, Model LCC 500, 2225 N capacity) to quantify pulling force and a potentiometer (Clarostat, Series 62 high precision 10 turn, 30 kΩ resistance) to give handle position. The distance between the handle and the ergometer drive gear ($L_h$) is determined from the output signal of the potentiometer mounted on the gearing system of the ergometer and from appropriate calibration information. The chain is assumed to move in a horizontal plane. The locations of the drive gear ($X_0$, $Y_0$) and the lateral aspect of the ankle ($X_{JC_a}$, $Y_{JC_a}$) are assumed to remain fixed in an inertial coordinate system having an origin located on the ground behind the rower (see Figs. 1 and 2). The pulling force exerted by the athlete on the rowing handle ($F_{handle}$) is determined from the force transducer.

Data collection is achieved using a computer (90 MHz Pentium processor) equipped with analog to digital converter (Keithly Metrabyte DAS 1802-ST), and custom designed software written using Visual Basic (Microsoft Visual Basic version 3.0 for Windows). The athlete's limb and torso lengths (i.e. $L_{leg}$, $L_{thigh}$, $L_{torso}$, $L_{arm}$, $L_{forearm}$) are required as input to the computer program and are recorded prior to a training session. The data acquisition system allows collection and processing of 8100 samples per channel. Typically, a sampling rate less than 200 Hz and a duration of 5–10 s are appropriate for studying rowing mechanics.

Data processing involves several steps. Assuming sagittal plane motion, a link segment model is used to locate each joint center throughout the rowing movement (see Fig. 2 and Eqs. (1)–(14)). The foot is assumed to be fixed to the ergometer footplate, thus fixed in inertial space. Handle and joint position data are smoothed using a 7-point moving average and then numerically differentiated to determine handle velocity and joint angular velocities, respectively. Numerical differentiation is based on a 2-point backward difference technique. The first data samples are not displayed as part of the feedback. The instantaneous power developed by the athlete is calculated by multiplying the handle force by the handle velocity. The average power per stroke is also calculated.

$$X_{JC_k} = X_{JC_a} - L_{leg}\cos(\pi - \varphi_a - \varphi_f), \tag{1}$$

$$Y_{JC_k} = Y_{JC_a} + L_{leg}\sin(\pi - \varphi_a - \varphi_f), \tag{2}$$

$$X_{JC_h} = X_{JC_k} - L_{thigh}\sin(\pi/2 + \varphi_k - \varphi_a - \varphi_f), \tag{3}$$

$$Y_{JC_h} = Y_{JC_k} - L_{thigh}\cos(\pi/2 + \varphi_k - \varphi_a - \varphi_f), \tag{4}$$

$$X_{JC_s} = X_{JC_h} - L_{torso}\cos(\pi - \varphi_h + \varphi_k - \varphi_a - \varphi_f), \quad (5)$$

$$Y_{JC_s} = Y_{JC_h} + L_{torso}\sin(\pi - \varphi_h + \varphi_k - \varphi_a - \varphi_f), \quad (6)$$

$X_h = X_0 - L_h$ (handle is assumed to move only horizontally), (7)

$Y_h = Y_0$ (handle is assumed to move only horizontally), (8)

$$L = ((X_h - X_{JC_s})^2 + (Y_h - Y_{JC_s})^2)^{1/2}, \quad (9)$$

$$\alpha = \tan^{-1}((Y_h - Y_{JC_s})^2/(X_h - X_{JC_s})), \quad (10)$$

$$\beta = \cos^{-1}((L^2 + L_{arm}^2 - L_{forearm}^2)/(-2\,L\,L_{arm})), \quad (11)$$

$$\theta = \alpha + \beta, \quad (12)$$

$$X_{JC_e} = X_{JC_s} + L_{arm}\cos(\theta), \quad (13)$$

$$Y_{JC_e} = Y_{JC_s} + L_{arm}\sin(\theta), \quad (14)$$

where

$L_h$ distance from the chain gear to the rowing handle

$L_{leg}$ length of lower leg (lateral malleolus to lateral femoral epicondyle)

$L_{thigh}$ thigh length (lateral femoral epicondyle to greater trochanter)

$L_{torso}$ torso length (greater trochanter to lateral aspect of shoulder)

$L_{arm}$ upper arm length (lateral aspect of shoulder to lateral aspect of elbow)

$L_{forearm}$ forearm length (lateral aspect of elbow to center of handle)

$L$ length from the shoulder to the handle

$\varphi_f$ angle between the foot and the inertial $x$-axis reference

$\varphi_a$ angle between the foot and the lower leg

$\varphi_k$ angle between the lower leg and the thigh

$\varphi_h$ angle between the thigh and the torso

$\varphi_e$ angle between the upper arm and the forearm (note: this angle is not used in the link segment analysis, but it is displayed in the feedback given in Fig. 3)

$\alpha$ angle between $L$ and horizontal

$\beta$ angle between $L$ and $L_{arm}$

$\theta$ angle between $L_{arm}$ and horizontal

$X_0$ the $x$ coordinate of the chain gear (assumed fixed in an inertial reference frame)

$Y_0$ the $y$ coordinate of the chain gear (assumed fixed in an inertial reference frame)

$X_{JC_a}$ the $x$ coordinate of the ankle joint center (assumed fixed in an inertial reference frame)

$Y_{JC_a}$ the $y$ coordinate of the ankle joint center (assumed fixed in an inertial reference frame)

$X_{JC_k}$ the $x$ coordinate of the knee joint center

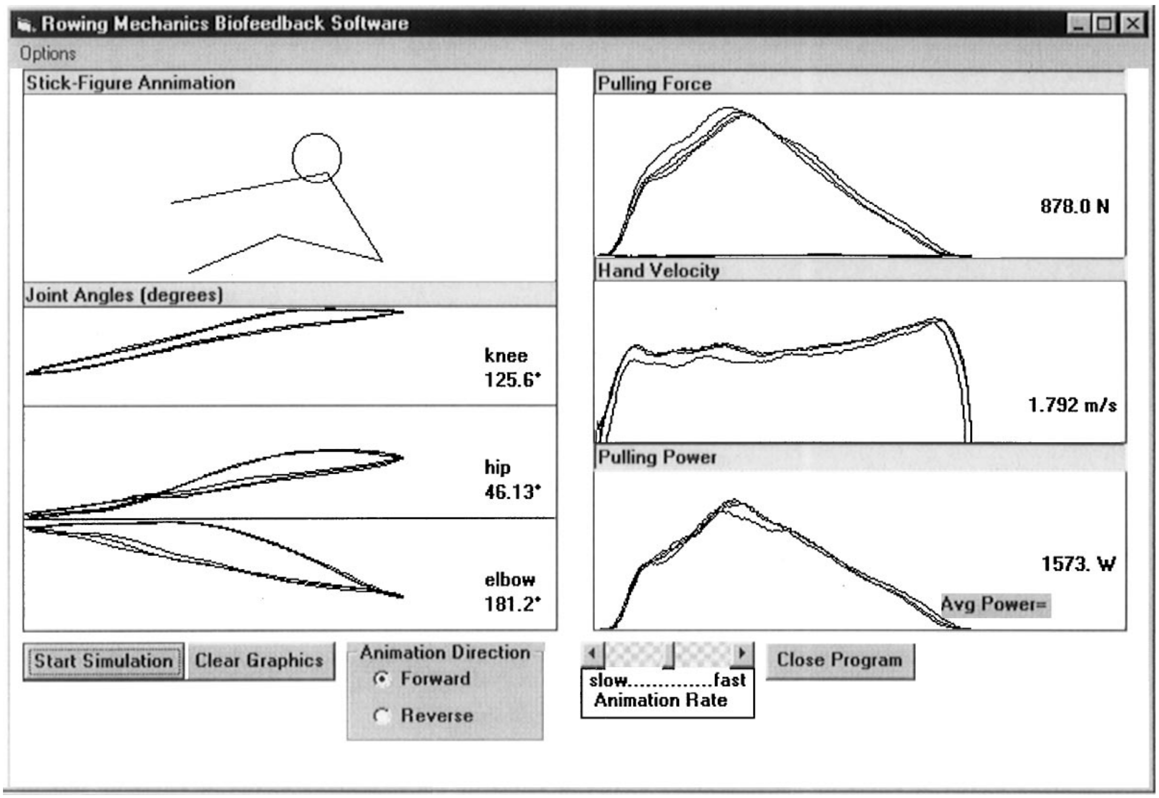


Fig. 3. An illustration of the feedback display given to the coach and/or athlete. A stick figure animation of the athlete is provided along with knee, hip, and elbow angles expressed as a function of the handle position. Pulling force, velocity and power are also displayed as a function of handle position.

$Y_{JC_k}$ the $y$ coordinate of the knee joint center
$X_{JC_h}$ the $x$ coordinate of the hip joint center
$Y_{JC_h}$ the $y$ coordinate of the hip joint center
$X_{JC_s}$ the $x$ coordinate of the shoulder joint center
$Y_{JC_s}$ the $y$ coordinate of the shoulder joint center
$X_{JC_e}$ the $x$ coordinate of the elbow joint center
$Y_{JC_e}$ the $y$ coordinate of the elbow joint center
$X_h$ the $x$ coordinate of the center of the handle
$Y_h$ the $y$ coordinate of the center of the handle

Following data collection and processing, a stick figure animation of the athlete is displayed on the monitor along with joint angles, handle velocity, pulling force, and pulling power expressed as a function of stroke position. Joint centers are used to construct the stick figure animation. Information can be displayed in a continuously scrolling mode at a variety of rates or paused at a given instant of time. The maximum computer graphics update rate is approximately 16.7 Hz. The stick figure animation rate depends on the data sampling rate and the computer update rate. If data are collected at 200 Hz (i.e. every 5 ms), then the fastest animation rate is approximately 8% that of real time (16.7 HZ 0.005 s 100).

The utility of the biofeedback system was investigated by testing a member of the University of California-Davis Women's Varsity eight-sweep team. The rower was instrumented as described above. She rowed at her self-selected race pace. Data were collected at 200 Hz for 5 s.

## 3. Results

The objective of this project was to develop a rowing instrumentation system capable of providing immediate feedback pertaining to both human movement characteristics and the force and power delivered to the rowing handle throughout a rowing stroke. The simplest way to demonstrate that such a system was achieved is to present the results provided to the athlete tested (see Fig. 3). The feedback displayed to the athlete included a stick figure animation, joint kinematics, pulling force, and pulling power. The stick figure, upper left-hand corner of Fig. 3, illustrates the configuration of the athlete's body midway through a power stroke. The stick figure provides a useful visual depiction of how the body moves throughout the rowing stroke and the body configuration that corresponds to the instantaneous kinematic and kinetic data being displayed. The stick figure is intended as a qualitative tool while the kinematic and kinetic data are intended to provide the quantitative information that the coach and athlete can use to study/evaluate rowing mechanics.

Kinematic and kinetic data are shown for three sequential rowing strokes (Fig. 3) and illustrate the utility of the quantitative information provided. Knee, hip, and elbow angles are shown below the stick figure with the vertical scale ranging between 0 and 180°. Pulling force, handle velocity, and power profiles are shown to the right of the stick figure. All data are graphed as a function of the horizontal position of the handle. These profiles illustrate the repeatability between strokes for this athlete. Profiles could easily be compared between rowers or before and after a technique modification for a specific rower. Further, the average power per stroke (lower right corner of Fig. 3) can be used in conjunction with the kinematic and kinetic profiles to identify movement strategies that maximize the average power output. Instantaneous values for the various quantities are shown in the lower right corner of each respective display box. Peak force, peak power, and average power values are comparable to values reported by Steinacker (1993) for a typical race in a single scull (e.g. peak force 500–700 N, peak power 1000–1600 W, power/stroke 600–900 W).

## 4. Discussion

This rowing instrumentation system integrates appropriate hardware and software to quantify and graphically display information about the rower's joint kinematics, pulling force, and pulling power. The force transducer measures forces to within $\pm 2$ N. The distance the handle moves is determined accurately to within $\pm 1$ mm. The electrogoniometers quantify joint angles to within $\pm 2°$. The software allows data acquisition, processing and display within a time frame appropriate for use during a single training session.

Potential limitations of the system include encumbered motion resulting from the use of electrogoniometers, electrogoniometer slippage, hip angle interpretation, and stick figure interpretation. The use of electrogoniometers provides direct measures of joint angles, which is desirable, but it also requires that they be attached to the athlete. Athletes tend to row cautiously at first, but then settle into their normal rowing mechanics within a few minutes. The electrogoniometers are attached to the limb segments using straps. On occasion these straps loosen resulting in slippage of the electrogoniometer and inaccurate joint angle measurements. Fortunately, it is usually obvious when this occurs and the electrogoniometer can be adjusted and secured.

The hip electrogoniometer measures the angle between the pelvis and the thigh. Video systems are often used to measure hip angle, defined as the angle between a line from the hip to the shoulder, and the thigh. Rowers flex and extend their back to different amounts, but generally the electrogoniometer will indicate a hip angle range of motion of 10–20° less than that determined using a video system. Both angles are relevant, giving slightly different information that may be useful for understanding rowing mechanics. Because hip angle reflects the orientation of the pelvis, the stick figure that is generated does not accurately reflect the location of the shoulder joint. The location of the shoulder joint on the stick figure may be in error by 10–15 cm horizontally and 2–3 cm vertically.

The stick figure is also affected by the assumption that the foot remains fixed to the footplate of the ergometer, and the sagittal plane representation of elbow angle. In reality the heel pulls off the footplate during the end of recovery and the start of the power stroke, translating approximately 2 cm in the horizontal direction and 4 cm in the vertical direction. The upper arm is displayed as moving in the sagittal plane, but this may not be correct if the athlete uses a horizontal shoulder flexion/extension movement. The stick figure animation was considered an important visual tool; but for the reasons stated above it should not be used for quantitative purposes.

This biofeedback system provides a unique tool for quantifying and displaying information about joint kinematics, pulling force, and pulling power as the rowing athlete trains. Such information is useful for identifying weaknesses in rowing technique or differences between different caliber athletes (Nelson and Widule, 1983; Smith and Spinks, 1995). It is anticipated that this system and the feedback provided will be modified as we gain experience and identify the key aspects to efficient and powerful rowing.

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