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THE UNIVERSITY OF SYDNEY
FACULTY OF EDUCATION
SCHOOL OF TEACHING AND CURRICULUM STUDIES

# THE IDENTIFICATION AND ENHANCEMENT
# OF
# BIOMECHANICAL PERFORMANCE VARIABLES
# IN
# MAXIMAL ROWING

A Thesis submitted by

Warwick Linley Spinks

in

Fulfillment of the Requirements for
the Degree of Doctor of Philosophy

1991

*"That is to say, for a given expenditure of energy, we can make our boats go faster. It is the old story; it is the man that counts. He is more important than rig or differences in boats and oars. It is worthwhile making him as efficient as possible both as an individual and in combination as a crew member".*

*(Edwards, 1963, p.87-88)*

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## ABSTRACT

Coach education programs in competitive rowing require consideration of the biomechanical principles influencing rowing performance. The extent to which this information may be utilized in the coaching process is not readily apparent. In phase one of this study, oar force and oar angle data resulting from a 6 minute maximal rowing ergometer test undertaken by novice ($\underline{n}$=9), state ($\underline{n}$=23) and national ($\underline{n}$=9) level male rowers, were used to identify biomechanical performance variables which could be used to accurately discriminate between rowers of differing ability levels. The variables included mean propulsive power output per kilogram of body mass (MPPO) (watts/kg), propulsive work consistency (PWC) (%), stroke-to-stroke consistency (SSC) (%) and stroke smoothness (SMO) (%). Discriminant function analysis indicated the presence of two functions both of which clearly indicated the importance of MPPO as a discriminating variable. Function two gave greater weight to SSC and SMO than Function one, however Function one was the most powerful discriminator. Classification procedures indicated that 100% of the national level rowers, 73.9% of the state level rowers, 88.9% of the novice level rowers and 82.9% of all rowers were correctly classified. Stepwise discriminant analysis included the variables in the order MPPO, SSC, SMO and PWC ($\underline{p}$<.001).

The last place addition of PWC in the stepwise discriminant analysis indicated that rowers, regardless of ability level, adopt a pattern of power output which reflects a lack of consistency in work output. However, even pace race strategy involving an invariant boat velocity and a constant pattern of power output is considered to be the appropriate strategy for high level rowing performance. Phase two of this study determined the extent to which an increase in PWC influenced improvement in MPPO. Kinetic information feedback (KIF) was used to modify the pattern of work output. Club level male rowers ($\underline{N}$=34) undertook two 6 minute maximal rowing ergometer tests. Following the first test (pretest) the subjects were randomly allocated to a control ($n$=17) or experimental ($n$=17) group. The posttest was conducted 7 days later during which the experimental group received concurrent KIF in the form of stroke-to-stroke force-angle profiles compared to a criterion force-angle profile template. Single factor MANCOVA indicated that the experimental group obtained significantly higher posttest scores for PWC ($M$=91.8,$F$[1,30]=9.82,$p$<.01) and MPPO ($M$=3.72,$F$[1,30]=4.20, $p$<.05). Coefficient of variation analysis for stroke rate, peak force and stroke length indicated that the experimental subjects used the KIF to maintain a more constant pattern of power output (increased PWC) and to increase MPPO.

The results of this study indicated that (a) biomechanical performance variables related to rowing capacity and skill may be identified and used to accurately discriminate between rowers of differing ability levels, (b) of these variables, PWC is the least effective discriminator, (c) KIF may be used to modify patterns of work output during maximal rowing and to enhance maximal rowing performance, (d) there is biomechanical support for the even pace race strategy in competitive rowing, and (e) examination of the force-angle profile may allow coaches to identify those biomechanical factors which limit rowing performance and which may assist the coach to determine the best available rowing technique and/or race strategy for a given rower.

Keywords: Rowing, biomechanics, performance, kinetics, information feedback.

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[(*) Photography by Dave Robinson, Cumberland College of Health Sciences, The University of Sydney.]

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# Chapter 1

# INTRODUCTION

## Coach education in Australia

The relatively poor showing of the Australian Olympic team at the 1976 Montreal Olympic Games and the confrontation between team members and the then Prime Minister of Australia, Malcolm Fraser, were the very public faces of Australia's decline as an international sporting power following a period of significant achievement from 1948 to 1972. Federal government involvement in Australian sport began with the Whitlam Labour government (1972-1975) but the events of 1976 and the resulting public outcry saw the Fraser Liberal government establish a ministry for sport and recreation, the Australian Institute of Sport and, indirectly, the National Coaching Accreditation Scheme.

In 1979 the (now) Sport and Recreation Ministers' Council established the Australian Coaching Council as a co-operative venture between Commonwealth, State and Territory governments and sports bodies. The principal role of the Council is the national development of sports coaching in Australia which includes responsibility for the National Coaching Accreditation Scheme. The Scheme aims to develop uniform coach education programs in individual sports covering three levels, viz.:

(1) General principles of coaching and human performance.

(2) Skills in particular sports, techniques, strategies and science.

(3) Practical instruction in coaching.

These programs aim to provide coaches with appropriate knowledge to ensure that Australian athletes are coached by competent personnel. The various national sporting bodies provide coaching education material for their particular sport for each level of the Scheme. The coach education programs emphasize the efficient conduct of training sessions, appropriate methods of instruction, technique correction, and methods of analyzing performance. Overall, the National Coaching Accreditation Scheme is a significant educational initiative given that:

(1) Of the development plans submitted by National sporting organizations to the Australian Sports Commission for funding, 70% have nominated coaching as a high priority.

(2) Some 71 sports have had coaching education programs approved at one or more levels.

(3) Over 7,500 coaches are now being accredited at various levels each year.

(4) As at 30 June 1988, 52,813 Australian coaches were accredited under the Scheme. These included 45,135 at level one, 6,730 at level two and 948 at level 3.

(5) In 1987-88 the Australian Sports Commission committed $1.706 million, or 27.5% of the Commission's Sports Development Program budget of $6.216 million to coaching. With other development

activities the Commission's contributions to sports coaching exceeded $2 million (Australian Sports Commission and Australian Institute of Sport, 1988).

## Coach education in Australian rowing

In 1981, the National Coaching Committee of the Australian Rowing Council was formed to implement a National Coaching Accreditation Scheme in rowing in Australia. The Level One course is aimed at coaches of novice and school crews and involves attendance at a weekend seminar following one year of practical coaching experience.

> This course is as much designed to warn coaches of the dangers of some ill advised practices often carried on by coaches as it is to develop technical knowledge (Boultbee, 1982, p.26).

Theoretical information for the course includes the Canadian Rowing Association publication "Rowing One" (Klavora, 1982a) which provides specific rowing information as well as the Australian Coaching Council publication "You're the Coach" (Nettleton, 1980) and videotape productions both of which deal with general coaching principles.

Level One coaching seminars focus on topics such as rigging, the use of video facilities, teaching sculling to novices and exercises to improve technique for both rowing and sculling (Boultbee, 1982). Level Two courses are intended for coaches who have considerable experience and who aspire to coach at a higher level (for example, GPS Head of the River, State or National School Championships, State or Australian

Championships).

> This course is expected to attract coaches prepared to spend a lot of time in the sport and wishing to develop themselves as coaches to the very top level (Boultbee, 1982:26).

The Level Two course involves a minimum of 60 hours with at least two seasons of practical experience required. The course involves about 50% of rowing content and 50% of general sporting and coaching principles covering such areas as exercise physiology, biomechanics and skill acquisition.

Keane (1983) stated that the information presented to a Level Two coach should include:

(1) Physiology and its application to land and water based training.
(2) Principles of skill acquisition and their application to rowing.
(3) Advanced technique of rowing and sculling and biomechanical principles.
(4) Racing strategy and applied psychology.
(5) Nutrition and fluid balance.
(6) Rigging of boats and adjustment to equipment.
(7) Planning of programs, both short and long term, to achieve specific competition goals.

Theoretical information for this course is provided by the Canadian Rowing Association publication "Rowing Two" (Klavora, 1982b) for the specifics of rowing with the "Towards Better Coaching" (Pyke, 1980) publication providing the general sports science information. In some circumstances State government sport and recreation agencies provide seminars concerning general coaching principles which are acceptable as long as the material presented in the seminars is closely tied to the material in "Towards Better Coaching" (Keane, 1983).

For the purposes of this study, it was necessary to examine the type of information being presented to rowing coaches in relation to the physiology of rowing, the biomechanics of rowing, skill acquisition in rowing, advanced technique of rowing and sculling and fault analysis in rowing. Some insight into the structure of the Level Two course was provided by Keane (1983) and is outlined below:

1. The physiology of rowing (2 hours) including, (a) the aerobic and anaerobic systems, (b) training of these systems, (c) physiological response to training, (d) physiological response to competition, and (e) field tests for the coach's use. Specific reference is made to Chapter 3 and 6 of "Towards Better Coaching" (Pyke, 1980).
2. The biomechanics of rowing (2 hours) including (a) Newton's laws, (b) momentum, (c) movement analysis, (d) levers, and (e) fluid mechanics and resistance.
3. Skill acquisition specific to rowing technique (1.5-2 hours) including (a) stages of skill acquisition, (b) feedback (when, how much, how precise), (c) components of the rowing task, (d) the oarsman/oarswoman as an information processor, (e) sensory domain,

(f) selective attention, (g) teaching the stroke, (h) consideration of backward chaining, and (i) correction of problems. Specific reference was made to Chapter 4 of "Towards Better Coaching" (Pyke, 1980).

4. Advanced technique of rowing and sculling (6 hours) including (a) analysis of the preferred style (catch, drive, release, recovery, approach to catch), and (b) principles of rigging (span, work through, height of work, pitch, weighting and balancing oars).
5. Faults and drills (2 hours) including (a) recognizing faults and drills to correct technique, (b) video presentation (sequence of faults, the drill, the "after look"), (c) video of the Australian crew practising various drills to improve technique, and (d) use of the ergometer to assist coaching against faults.

As indicated above, the coaching education program adopted by the Australian Rowing Council requires consideration of many aspects of the human movement/sports science disciplines as well as attention to the technical aspects of rowing. While in many respects this is a desirable strategy, given that all knowledge is good knowledge, the extent to which coaches can or are encouraged to integrate the relevant information to develop an overall view of the demands of rowing and how an individual rower's needs are related to these demands, is not readily apparent. Therefore, the overall aim of this study was to demonstrate how this information integration process may be used to assist in the improvement of rowing performance.

## The sport of rowing

Rowing is different from other forms of human exercise in that the body is supported by a moving seat and both the arms and legs are involved with the two legs working in the same phase. This contrasts with running for example, during which one leg is predominantly performing work at a time (Secher, 1983). Rowing has been described as "an intermittent-type activity, in which a period of intense effort, mainly in the legs, back and arms, is followed by a slightly longer recovery phase as the oarsman comes forward to take the next stroke" (Fukunaga, Matsuo, Yamamoto and Asami, 1986, p.474).

Boat motion occurs as a result of the manipulation of the oar(s) by the rower. Force is applied to the oar by the extensors of the lower limbs and trunk, and the flexors of the upper limbs. While there are a number of different rowing styles, the pulling force on the oar is generally instigated by lower limb action and then continued by arm and trunk action. During the stroke, the oar handle moves through a distance ranging from 1.4 to 1.6 metres. During the recovery phase of the stroke, the blade of the oar is turned horizontally to the water ("feathered") so as to reduce air resistance. Adopted stroke rates depend upon rowing style, training status, competition level and the point of progress of a race, but are generally within the range of 30 to 40 strokes per minute.

Rowers may participate in two categories of rowing depending on how many oars the rower uses. In sweep oar rowing, each rower uses one oar which is approximately 3.8 metres long with a blade area of 1000 square centimetres. Within this category rowers may row in crews of eight, four and two rowers. The four oar and pair oar crews may or may not utilize the services of a coxswain whose primary task is to steer the boat. Rowers are referred to as bow or stroke side rowers depending on which side of the boat their oar extends from. Bow side oars extend to starboard (to the left of the rower) whilst stroke side oars extend to port (to the right of the rower). Stroke side rowers occupy the even numbered seats whilst bow side rowers occupy the odd numbered seats, the first of which is the seat closest to the bow of the boat. This arrangement can be varied considerably depending on the experience and capacity of the crew.

The other rowing category is sculling where the rower (or sculler) has two sculls. These oars are about 3 metres long with each blade having an area of 700 square centimetres. Scullers may participate in single pair or quadruple sculls none of which utilize a coxswain. While there are many similarities between the dynamics of sculling and sweep oar rowing, the differences are such that this study focused on sweep oar rowing only.

The rower sits on a seat which rolls on wheel which in turn roll on two tracks (or slides). These slides are approximately 65 to 75 centimetres in length and allow compression forces to be generated in the lower limbs. The rower's feet are placed in adjustable foot stretchers that are attached to the hull. The rower's work output via the oar is transmitted to the boat through a vertical swivel (or thole) pin which is attached to the outermost portion of a stainless steel (or hard alloy) rigger, and to a moveable oarlock (or "swivel") which rotates around the thole pin and into which the oar is introduced and held in place by a moveable bar (or "gate"). The position of the swivel can be varied according to the rower's span, work through, pitch and height requirements. The position of the oar in the swivel is stabilized by the use of a ridge (or "button") on the shaft and the surface of the oar in contact with the swivel is protected by a plastic ferrule (or "leather"). The placement of the button determines the relative inboard and outboard oar lengths and thus the leverage characteristics of the oar. The relationship between the inboard oar length and the distance from the keelson to the thole pin (or "span") is considered when determining the position of the oar handle.

The hull cross section of a boat represents a slightly flattened circle. Depending on the type of boat, draft varies from 20 to 25 centimetres with crew on board. The hulls are designed so that (a) the wetted surface area of the loaded boat in proportion to the displacement, is as low as possible, (b) there is minimal wave formation during boat motion, and (c) strength, rigidity and stability are consistent with maximum weight reduction (Dal Monte and Komor, 1988; Nelson and Widule, 1983; Pannell, 1972). The main features of the sweep oar rowing boat are presented in Figure 1.

To obtain maximum rowing performance it is necessary to maximize concurrently both the forces generated by the rower and the effectiveness with which these forces are executed. In order to study these variables it is possible to divide the rowing stroke into four parts namely the catch, drive, finish and recovery phases (see Figure 2). The catch is the position where the oar is placed in the water at the commencement of the drive phase. The rower has reached the top of the slide, the legs are compressed with the arms and body extended forward. The boat experiences maximum deceleration at this point. The drive phase sees the oar propelled through the water as the legs are extended, the body leans backwards and the arms are drawn into the chest. The finish occurs as the legs, body and arms reach the end of the drive phase and the oar is released from the water. The recovery (or return) is the reverse of the drive phase and is executed from when the oar is extracted from the water to the point where it is about to enter the water again. The drive component of the rowing cycle (from catch to finish) represents 60% of the total stroke cycle (from 30% to 90% of the cycle) whereas the recovery component represents the first 20% and the last 10% of the rowing cycle (Wilson, Robertson, and Stothart, 1988).

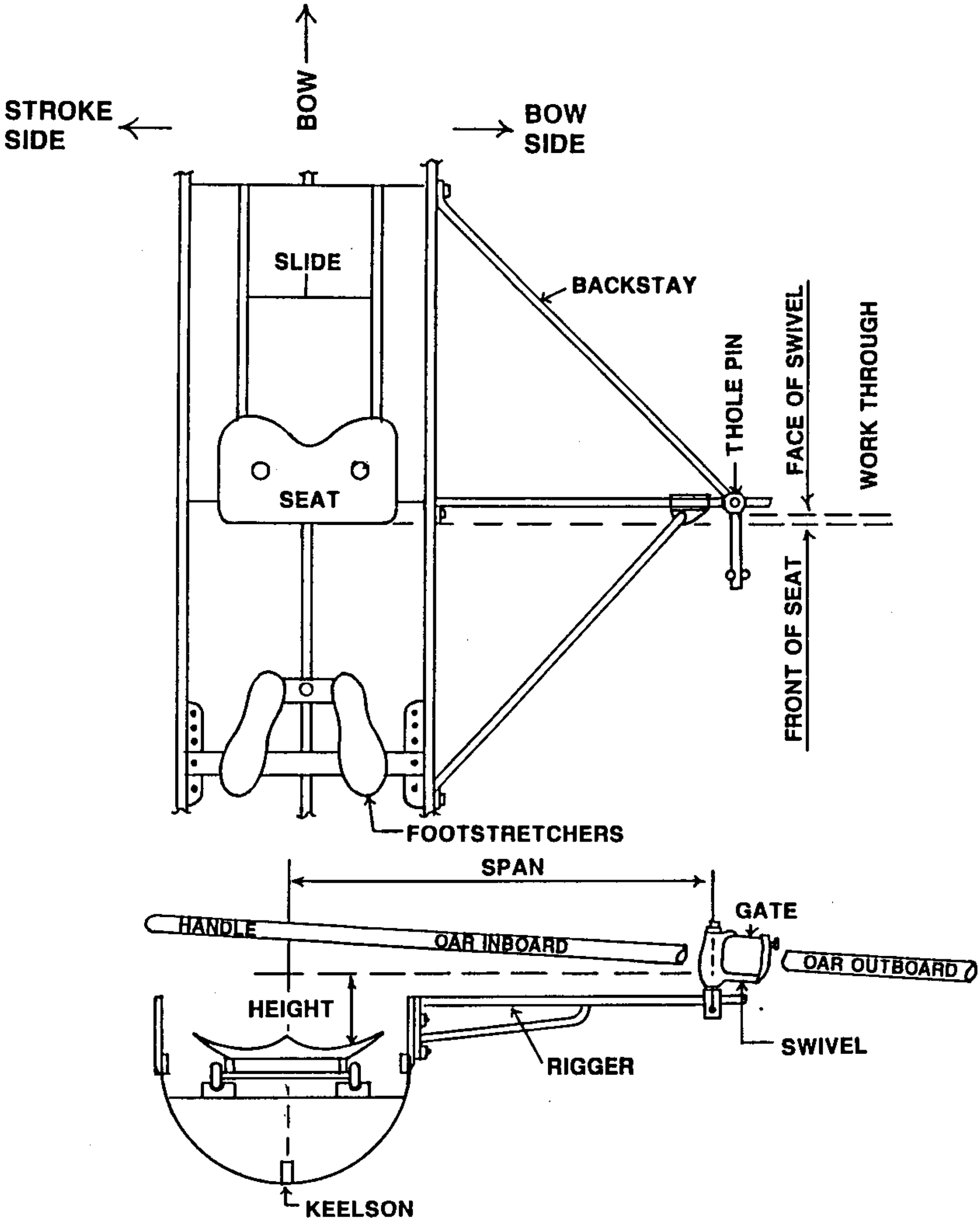


Figure 1   The main features of the sweep oar rowing boat

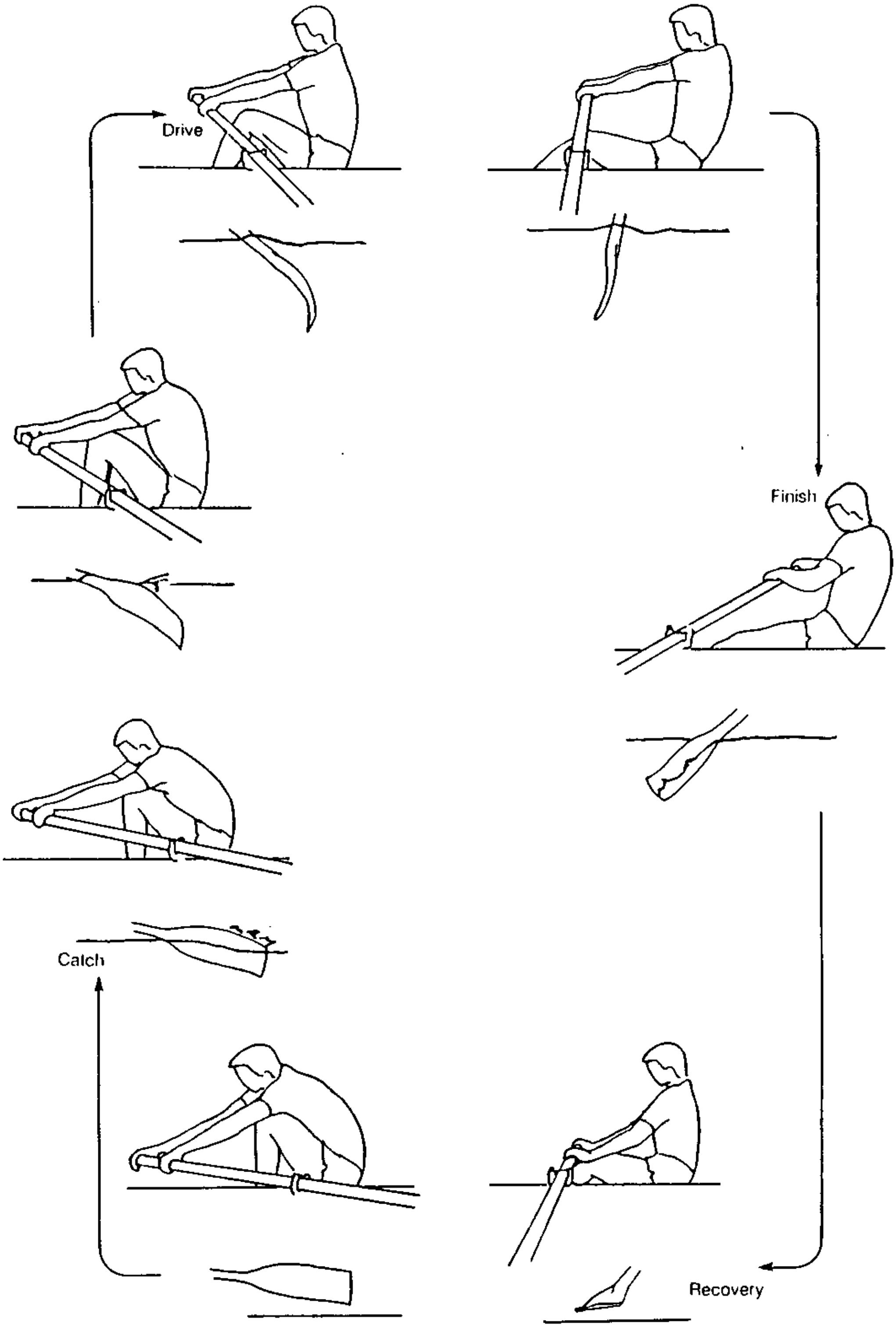


**Figure 2** Components of the rowing stroke showing oar handle and blade position (adapted from Klavora, 1982a)

The rower and the boat need to be considered as an interactive system throughout all phases of the stroke. As the rower moves up the slide the centre of mass of the system decelerates smoothly. This action causes the boat to accelerate in the direction of motion of the boat. The velocity of the boat relative to the water is greatest during this part of the stroke while air and water resistance (drag) act on the boat and air resistance acts on the oar and the rower's body to decelerate the system (Klavora, 1982a; Leighton, 1983; Nelson and Widule, 1983).

The peculiar nature of the boat-oar-rower mechanical system, the influence of sliding masses, the interchange between oar and water and the inherent physiological demands make rowing a unique sports discipline and serve to create a number of problems of interest to the human movement/sport scientist. Of particular interest in this study was the force exerted by the rower on the oar handle.

Forces in rowing are generated by the rower within the confines of the man-machine relationship. The extent to which the rower can influence the forward motion of the boat depends on the magnitude of the applied force and the distance through which the force is applied. The force-angle profile allows examination of the force applied by the rower at each stage of the stroke as well as the rate of work output for a specific effort (see Figure 3). The force-angle profile is derived by plotting the force applied by the rower on the oar handle against the oar angle. The applied force, however, is not constant throughout the duration of the stroke, the force generated being a function of muscular strength and body configuration. Leg, back and arm movements all combine to provide the stroke length and the force at each part of the stroke (Leighton, 1983; Pannell, 1972).

In general, the coaching and teaching of the rowing stroke has centred around visual analysis of the relationships between the oar, the boat and the rower's body. The quality of these relationships may be referred to as the aesthetics of rowing technique and represent the criteria by which rowing performance is judged. The assumption being that appropriate aesthetic characteristics result in the creation of reaction forces on the oar blade that produce the most effective propulsion. This approach has resulted in a variety of instructional strategies for the development of rowing technique. While these strategies focus on the mechanics of the rower operating in the boat (Klavora, 1982a; 1982b) visual analysis of what is happening between the oar and the water may not allow the coach to accurately quantify or analyze the stroke. Therefore, there is a need to examine the characteristics of the external forces acting on the oar to determine if the rower is performing efficiently (Angst, 1980; 1984; Rushall and Jones, 1984; Smith, Spinks and Moncrieff, 1988).

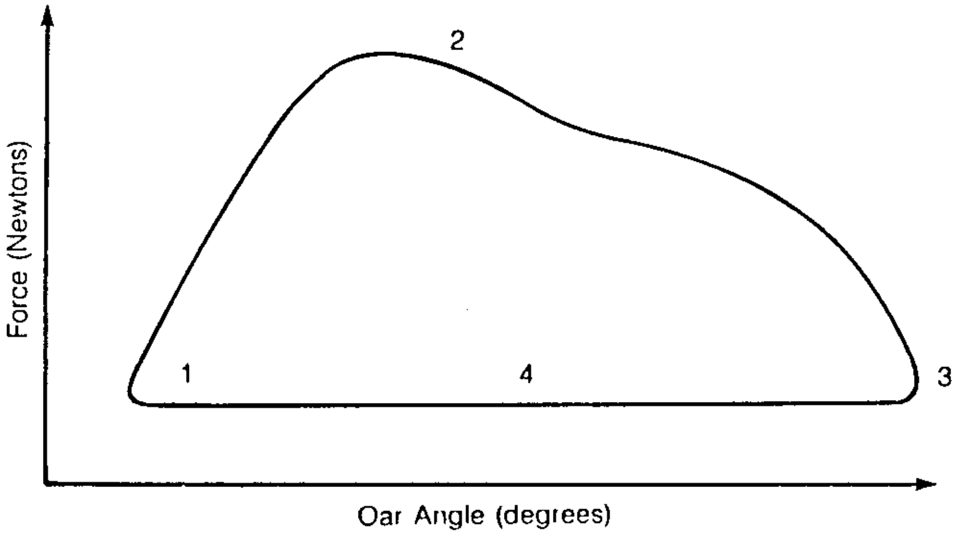


**Figure 3** Characteristics of the force-angle profile
1 = catch, 2 = drive, 3 = finish, 4 = recovery

## Sport biomechanics and performance enhancement

Biomechanics as it is applied to the study of the techniques utilized by humans in sport activities is defined as "the science concerned with the internal and external forces acting on a human body and the effects produced by these forces" (Hay, 1985, p.2). These forces whether static, or kinetic determine what is commonly referred to as the performer's technique. Sports biomechanics is a discipline used by the physical education teacher or sports coach to assist the individual to perform with greater speed, power, effectiveness, and in some instances, efficiency which is the prime component of effectiveness. Much of the sports biomechanics literature is descriptive in nature with research focusing on the movement patterns associated with particular sports (Dessureault and LaFortune, 1981; Elliott, 1985; Elliott, Overheu and Marsh, 1987; Milburn, 1982; Nelson and Pike, 1978; Samson and Roy, 1976; Stoner and Ben-Sira, 1981). The underlying rationale of this research is based on the assumption that once specific movement patterns have been identified, coaches and teachers can use this information to effect technique correction and enhance performance.

While the volume of research in sports biomechanics indicates the value of this type of research to the human movement/sports science community there are certain difficulties associated with the recognition and optimization of human movement patterns (Hay, 1985). While sport biomechanics allows both quantitative and qualitative assessment of motor tasks (Kreighbaum and Barthels, 1985) teachers and coaches have difficulty in conveying information about movement patterns derived from biomechanical analysis because the patterns are influenced by anatomical, physiological, motor control and kinetic (physical) constraints. Therefore, most teachers and coaches must rely heavily on experience, intuition and trial-and-error to bring about significant performance variation. It remains therefore, for sports biomechanics to cast more light on the relationship(s) between biomechanical performance variables which influence sports performance.

Sports science is largely concerned with the identification of variables that are necessary for competitive excellence. It is generally accepted by coaches and sports scientists working in the sports education and sports science fields that "overall performance in a particular sport is related to a potentially identifiable set of basic performance variables each of which carries a certain relative importance for that activity" (Pollock, Jackson and Pate, 1980, p.522). There is both qualitative and quantitative support for this approach with the task being to determine the existence of relationships between criteria of sports performance and predictor variables such as basic motor abilities, anthropometric characteristics and biomechanical, physiological and psychological factors (Disch and Morrow, 1979).

The development of the concept of national rowing teams in the 1960s led to an upsurge of interest in the elite rower, the aim being to determine the characteristics of rowers who are successful in the international rowing arena. This information is seen as providing a better understanding of the demands of the sport, allowing the coach to learn more about the elite rower in general, revealing deficiencies in a rower's performance (physiological) profile and acting as a useful adjunct to the training programme (Mickelson and Hagerman, 1982). While there has been considerable interest in the anthropometric and physiological characteristics of successful rowers (Bloomfield, Blanksby and Elliott, 1973; Hagerman, 1984; Larsson and Forsberg, 1980; Morton, Lawrence, Blanksby and Bloomfield, 1984; Pyke, Minikin, Woodman, Roberts and Wright, 1979; Secher, 1983; Williams, 1977, 1978) it remains to be determined if the research model referred to above can be used to identify the combination and relative importance of biomechanical variables related to force-angle application in maximal rowing performance.

## The demands of competitive rowing

Competitive rowing is considered to be one of the most demanding continuous endurance sports (Larsson and Forsberg, 1980; McKenzie and Rhodes, 1982; Di Prampero, Cortili, Celentano and Cerretelli, 1971). Elite level rowers are invariably large individuals with very high aerobic work capacities (Cunningham, Goode and Critz, 1975; Hagerman, Connors, Gault, Hagerman and Polinski, 1978; Hagerman, Hagerman and Mickelson, 1979; Szogy and Cherebetiu, 1974; Wright, Bompa and Shepherd, 1976). Unlike athletes in other continuous endurance sports, rowers begin a race with a maximal effort that may extend for 45 seconds (McKenzie and Rhodes, 1982) At this stage of a race, elite eight oared male crews rate between 40 and 50 strokes per minute covering the first 250 metres. This (unique) initial effort generates considerable circulatory adjustment (Hagerman, 1984; Mahler, Nelson and Hagerman, 1984; Secher, 1983) and is followed by a 4 to 5 minute "middle" period of continuous high intensity work during which the rower reportedly recruits some 220-280 high tension muscle contractions (Larsson and Forsberg, 1980). During this phase, crews normally stroke at between 34 to 38 strokes per minute. This constitutes "high order" work or "short, heavy" exercise (Gollnick, 1982) and is particularly reliant on anaerobic energy sources with the rower operating at or near maximal oxygen debt capacity (Hagerman et al. 1978).

Tactical manoeuvres may place further demands on the oxygen transport system, for example, crews may insert a "spurt" during the middle phase of the race which normally consists of a stroke rate of 43 to 44 strokes per minute for 20 to 30 strokes. When these efforts are added to a final sprint to the finish over the last minute it is apparent that a "unique and very high demand is placed on the contractile mechanisms as well as on the oxygen utilizing capacity of the working muscles" (Larsson and Forsberg, 1980, p.239). It is not surprising therefore, to find that maximal aerobic power combined with muscular strength and endurance are requisite physiological capacities for rowing performance (Hagerman et al. 1978; Jackson and Secher 1976; Di Prampero et al. 1971).

Secher (1983) calculated the metabolic cost of rowing at racing speed to be 6.38 litres of oxygen per minute for elite heavyweight male rowers. In determining this figure it was assumed that rowing velocity is very nearly constant throughout a race. Secher claimed that the maintenance of an average velocity throughout the race would be the most economical way to complete the 2,000 metres. In fact, the velocity varies considerably, with the highest values recorded at the beginning of the race, followed by lower values over the next 1500 metres and increased values near to the average velocity, for the last 500 metres (Secher, Espersen, Binkhorst, Andersen and Rube, 1982).

One possible explanation for the initial spurt at the beginning of the rowing effort may be psychological. Rowers do not face their intended direction of travel and therefore, must establish a leading position in order to view opposing crews. This strategy does not explain however, why rowers use a similar work pattern when undertaking maximal efforts on a rowing ergometer (Hagerman et al. 1978; Schneider, 1980; Secher et al. 1982). Another possible explanation is a physiological one in that total oxygen uptake and work output for a given amount of exercise are stated to be greater when an initial spurt is performed in comparison to a constant (average) work load (Secher et al. 1982).

It is claimed (Secher et al. 1982) that rowers can perform this initial spurt without an increase in the total anaerobic metabolism as measured by the size of the oxygen debt and the blood lactate concentration. However, recent examination of the classical oxygen debt theory (Gaesser and Brooks, 1984) indicated that post-exercise oxygen debt and lactate metabolism may not adequately represent anaerobic metabolism during exercise.

In order to successfully undertake their unique work pattern, rowers must develop the ability to tolerate low muscle and blood pH values by increased buffering of lactate and increased psychological adjustment to a severe discomfort level (Telford, 1985). During a maximal rowing effort there is rapid development and continuing increases in blood lactate concentration (Howald, 1983; McKenzie and Rhodes, 1982). When the blood lactate concentration exceeds 3 to 5 millimoles per litre, lactate production exceeds removal (Telford, 1985) and therefore, the rower must endure high concentrations of blood lactate for approximately 90% of the effort (Howald, 1983). The resulting power output decreases relative to blood lactate accumulation reflecting a lack of consistency in work output.

It has been proposed (Klavora, 1982b) that rowers adopt an even pace or "best performance" race strategy when opposing crews of superior ability or when attempting to lower qualifying times for national crew selection. This race strategy is based on the maintenance of a constant boat velocity and maximization of the aerobic energy component with maximum "oxygen debt" and maximal lactate values occuring at the finish of the race. However, it is likely (Hahn, 1985) that the anaerobic energy pathways may play a greater role in energy provision for maximal rowing than previously thought.

Anaerobic glycolysis provides energy at a rapid rate and the rower must be capable of fully utilizing this energy source. This includes, the ability to tolerate very high concentrations of lactic acid. Given that the methods used in the assessment and training of lactic acid tolerance skill need considerable investigation (Hahn, 1985), it would appear that the question to be addressed is whether power output during maximal rowing can be improved by ensuring a more consistent work output pattern. However, prior to any examination of the need to modify an existing work or movement pattern, it is necessary to understand the nature of task.

## Rowing : The nature of the task

Rowing is characterized by extended movement sequences with little or no pause between sequences, therefore, it may be categorized as a continuous skill. Such skills are usually learned more rapidly than discrete skills and are usually retained for much longer because repetitions of the movement, leading from practice to over-learning, are an inherent part of the skill (Stallings, 1982).

Skill is also characterized by its consistency from occasion to occasion (Kelso, 1982). Rowing requires the highly consistent execution of an efficient movement pattern for each individual and while rowing coaches may strive for high levels of movement consistency through extended trials, this practice does not necessarily take into account whether the desired movement is the most biomechanically efficient for the individual. Therefore, even while skilled rowers demonstrate high levels of consistency, the actual movement patterns may not be efficient for that individual.

A high degree of dependence between successive movements also characterizes rowing skill. Thus rowing may be referred to as a highly coherent skill. The more coherent a motor skill, the more difficult it is to isolate the component parts for instruction and practice purposes while at the same time maintaining its integrity as a specific skill (Stallings, 1982). For example, an effective drive phase in rowing depends not only on the skilful placement of the oar in the water at the catch and the application of the required force on the oar handle but also on the passage of the oar through the release and recovery phases. Therefore the arbitrary splitting of skills into subskills may lead to erroneous practice.

Despite the fact that the rower has limited time to prepare for each movement sequence, with the body and the boat being in relative motion, the relationship between the rower and the boat is a stable one with the rower producing highly repetitious movement patterns. Rowing may therefore, be referred to as a self-paced skill. However, the demands of interacting with other crew members and competition from other crews during a race may be interpreted as introducing an element of external pacing. Given similar ability levels in a crew and a pre-determined race plan (including stroke rates) rowing would occupy the self-paced end of the pacing continuum. As motor skills move from being externally paced to self-paced the more likelihood there is that the essential requirements for likely success in that activity will be recognized (Fitts, 1964). This does not mean however, that the essential elements of externally paced skills cannot be recognized and taught, only that increased variability in initiated movements and responses leads to reduced precision in element identification.

Rowing may also be categorized as a closed skill. That is, the performance of rowing skill is controlled by a single set of environmental conditions requiring the development of a highly consistent movement pattern.

## The acquisition of rowing skill

Motor skill performance involves the utilization of selected neuromuscular actions in the pursuit of a specified motor objective. In the early stages of motor skill acquisition, the performer must understand the nature of the task and its demands, the movements that will realize the goal and the techniques that will work best to produce the necessary movements. This phase of motor skill learning was identified by Fitts (1964) as the early or cognitive phase during which the performer attempts to match an already developed repertoire of motor skills, with the demands of the task at hand. Continuing practice sees the performer enter what Fitts called the intermediate or associative phase. During this phase the performer demonstrates relatively well co-ordinated movements with fixed spatial and temporal organization and a more fully developed motor program (Sage, 1984).

The final or autonomous phase of skill acquisition (Fitts, 1964) is characterized by highly organized spatial and temporal aspects of the skill, increasing autonomy for the component processes and increased motor program length and integration. With automation of the motor program performers become increasingly introspective about the component parts of the movement pattern (Sage, 1984). Increasing practice in the autonomous phase results in less attention being given to movement execution (Stelmach, 1980) allowing the performer to attend to other stimuli in the environment. The more highly skilled the learner the greater the ability to selectively attend to relevant stimuli (Welford, 1968).

In this stage of the learning of closed motor skills, the main emphasis is on refinement of technique with practice involving repeated efforts to produce the correct movement pattern. For the teacher or coach, this phase involves the challenge of designing practice activities so that the performer continues to refine the movement pattern, receives appropriate feedback and is motivated to continue practice. The role of the teacher/coach is to act as a movement diagnostician and prescriber in order to detect errors and to vary movement patterns for greater proficiency (Sage, 1984; Yelon, Hoban and Perles, 1980). In order to do this, the rowing coach needs to understand the characteristics and demands of the rowing task as well as the principles of effective instruction. The intervention of the teacher/coach introduces a level of subjectivity into the assessment of rowing performance with the possibility of discrepancies occurring between actual and perceived movements (Angst, 1984). Therefore, there is a need for the provision of objective information feedback for accurate error detection and correction.

## Information feedback and motor skill acquisition

The exact characteristics of existing human motor learning theories vary according to the particular beliefs of the theorist (for example, Adams, 1971; Bartlett, 1958; Bernstein, 1967; Bruner, 1971; Gentile, 1972; Pew, 1974; Schmidt, 1975) however, one particular characteristic is common to all of these theories. This characteristic is the performer's use of feedback to modify performance so that relevant motor behaviours may be acquired in the pursuit of a specified movement objective. Movement produced by a performer results in response-produced feedback which is received by the interoceptive receptors and which provides information about the kinetics and kinematics of the movement. When the movement has been completed the performer can receive movement outcome information through the connate exteroceptive receptors or through human intervention (Marteniuk, 1986).

In certain motor tasks, input from sensory modalities may be limited or performers may be restricted in viewing their own movements. Proprioceptive information may be augmented by providing information not normally available during execution of the task, or through improving the quality of the available sensory feedback (Newell, Morris and Scully, 1985a). Augmented concurrent feedback has been shown to be effective in improving performance under both of the above conditions (Adams et al. 1972; Carrol and Bandura, 1982; Smith, 1966).

Considerable research effort has been expended on analysis of the principles controlling the acquisition of motor skills (Adams, 1987). There is general agreement that, apart from practice itself, information feedback is one of the most important variables influencing motor skill acquisition (Bilodeau and Bilodeau, 1961; Newell, 1976; Salmoni, Schmidt and Walter, 1984; Schmidt, 1988). One form of information feedback, termed knowledge of results, has long been considered the most potent form of information feedback. Knowledge of results allows a performer to examine the outcome of an action in relation to an externally defined goal (Newell and Walter, 1981; Newell, Quinn, Sparrow and Walter, 1983). This form of feedback is augmented, generally verbal (or verbalizable) and it is usually presented as post-response (or terminal) information (Salmoni et al. 1984; Schmidt, 1982; Wulf and Schmidt, 1989). Knowledge of results is believed to guide the learner to the goal action (Adams, 1971), to increase schema defining capability for novel movements (Schmidt, 1975) and to assist in the establishment of permanent memory capabilities (Wulf and Schmidt, 1989).

While there has been considerable investigation into the effects of knowledge of results (Adams, 1971, 1987; Newell, 1976; Salmoni et al. 1984) it is apparent that the performer is only appraised of what happened relative to the outcome of an action. There is no information concerning how the action was completed. Information about the movement generated is important to the performer particularly where the goal of the task is to produce a set movement pattern as is the case in many closed motor skills.

Augmented information about the performer's own movement pattern has been labelled knowledge of performance (Gentile, 1972) and includes feedback about movement kinematics and kinetics (Newell and Walter, 1981; Newell et al. 1985a). There is a body of opinion which suggests that traditional knowledge of results may not provide the necessary information feedback for performance optimization in a variety of motor skill activities (Fowler and Turvey, 1978; Gentile, 1972; Newell and Walter, 1981; Poulton, 1957). Information feedback related to the outcome of an action may take a variety of forms, each of which is characterized by one of the physical dimensions of time, length and mass. Knowledge of results research has usually focused on time and length by providing the performer with information feedback about either the time taken to complete an action sequence or the displacement of the movement. The majority of motor tasks utilized in this research were unidimensional in nature and required responses appropriate to single criteria such as position, time or accuracy. While these tasks have demonstrated the value of knowledge of results feedback (Newell, 1976; Stewart, 1980; Whiting, 1969), inferences made from this research do not transfer readily to multidimensional motor skills which require responses to temporal and spatial criteria and thus produce additional kinematic or kinetic constraints (Sanders, 1985). Therefore, a complete description of the movement pattern requires consideration of kinematic or kinetic information feedback parameters (Newell and Walter, 1981). Kinematic information feedback parameters include displacement, velocity and acceleration values whilst mass, force and time values represent kinetic information feedback parameters. Despite the extensive use of these measurements in sports biomechanics research, there has been only limited examination of the potential of these parameters for information feedback purposes (Newell and Walter, 1981; Newell et al. 1983).

A number of experiments have recently been conducted to compare the effects of kinetic and kinematic information feedback with knowledge of results in the acquisition of single degree of freedom discrete responses (Newell and McGinnis, 1985; Newell, Morris and Scully, 1985a). This research indicated that it is the task criterion that determines the nature of the information feedback in that the information feedback must correspond with the constraints imposed upon the response output. Therefore, in situations where the task criterion calls for a specific response trajectory instead of a knowledge of discrete outcome of the response, then kinematic or kinetic information has been shown to improve performance to a greater extent than knowledge of results (Newell and Carlton, 1987).

Kinetic information feedback has been shown (Newell, Sparrow and Quinn 1985b) to be superior to knowledge of results when a continuous force-time curve rather than a discrete force value has been used to represent the task criterion. The learning of a rapid arm movement has been found to be facilitated by kinematic information feedback (Newell, et al. 1983). Along with the earlier work of Hatze (1976) and Howell (1956) these studies have shown the potential of kinetic and kinematic information feedback and have served as a focus point for the development of an optimal configuration for augmented information feedback (Newell and McGinnis, 1985; Newell and Walter, 1981).

As pointed out by Newell and Carlton (1987) most of the studies mentioned above presented augmented information feedback in combination with a representation of the task criterion. This experimental design allowed the subject to observe the response just generated and to gauge the type and extent of movement pattern errors. The effect of augmented information feedback was found to interact with task and organismic constraints in assisting skill acquisition (Newell and Carlton, 1987).

Kinematic and kinetic parameters have been used for terminal (English, 1942; Hatze, 1976; Howell, 1956; Newell and Walter, 1981; Newell et al. 1985b; Newell et al. 1983) and augmented concurrent feedback (Lionvale, 1977; Sanderson, 1986a; Stevens, Kalikow and Willemain, 1975; Warren and Lehmann, 1975) in motor skill learning. The use of kinematic and kinetic information feedback in laboratory and certain field situations has been facilitated by recent developments in signal and data processing technology (Komor and Leonardi, 1988; Newell and Walter, 1981; Sanderson, 1986b). Previous attempts to utilize modern technology for information feedback may have been restricted by inadequate experimental techniques as well as a number of conceptual limitations regarding the value of videotape in motor skill performance and learning (Newell and Walter, 1981).

Despite these concerns a large number of researchers have shown interest in the variety of ways in which information feedback can be presented (Salmoni et al. 1984). It is believed that the utilization of kinetic and kinematic variables as information feedback can significantly influence the acquisition and optimization of motor skills (Broker, Gregor and Schmidt, 1989; McLean and LaFortune, 1988; Newell et al. 1983; Newell et al. 1985b; Sanderson, 1986a).

Further research in this field should seek to firmly establish the benefits to be derived from utilizing modern technology for information feedback in motor skill performance and acquisition. The results of this research may serve to influence contemporary wisdom regarding the ways in which the performer utilizes available information in carrying out a motor task, as well as facilitating recognition of the movement parameters inherent in the motor programme (Newell and Walter, 1981).

## Statement of the problem

Specifically, this study aimed to:

(a) Identify a number of biomechanical performance variables based on an analysis of oar force and oar angle data which could be used to provide accurate discrimination between rowers of differing ability levels and which could provide meaningful feedback for rowers and their coaches.

(b) Determine the effects of increased propulsive work consistency on mean propulsive power output per kilogram of body mass during maximal rowing.

## Research hypotheses

For the purposes of this study it was assumed that a real-time force-angle profile measurement and analysis system could be developed for maximal ergometric rowing. It was also assumed that this system could be used to identify and enhance biomechanical variables of importance to maximal rowing performance. It was hypothesized that:

(1) Biomechanical performance variables derived from oar force and oar angle data during a maximal ergometric rowing effort will effectively discriminate between rowers of differing ability levels. The biomechanical performance variables of interest being mean propulsive power output per kilogram of body mass, propulsive work consistency, stroke-to-stroke consistency and stroke smoothness.

(2) Of the above variables, propulsive work consistency will be the least effective discriminator between rowers of differing ability levels.

(3) Kinetic information feedback of stroke-to-stroke force-angle profile characteristics compared to a criterion force-angle profile template will significantly increase propulsive work consistency during maximal ergometric rowing.

(4) Rowers who utilize kinetic information feedback in order to significantly increase propulsive work consistency will demonstrate a significant increase in mean propulsive power output per kilogram of body mass during maximal ergometric rowing.

## Significance of the study

The controlled environment provided by the rowing ergometer allows a ready comparison of performance between rowers as well as providing useful feedback to the individual rower. However, most ergometers are only able to provide information related to work output and stroke rate and ignore skill factors such as consistency and technique. The predictive capacity of ergometer tests and the quality of feedback provided to individual rowers can be improved by measuring aspects of rowing skill as well as raw output. A number of relevant variables are accessible through the force and angle information available from a sweep oar rowing ergometer. For example, the accuracy with which the rower traces the force-angle profile stroke after stroke (stroke-to-stroke consistency), the smoothness with which the force is applied during the drive phase of the stroke (stroke smoothness) and the "flatness" (or evenness) of the power output curve (propulsive work consistency) are all variables which can be derived from force-angle data.

Maximal ergometer testing is a regular feature of training and selection programs for competitive rowers. It is generally believed by rowing coaches and sport scientists that such tests are useful for identifying rowing capacity and skill. It is arguable that rowing performance is closely related to an identifiable set of biomechanical variables that may be weighted to reflect relative performance.

Limited use has been made of biomechanical analysis for discrimination purposes in rowing, therefore, the purpose of phase one of this study was to evaluate and quantify biomechanical differences among groups of rowers. Biomechanical variables of interest were mean propulsive power per kilogram of body mass, propulsive work consistency, stroke-to-stroke consistency and stroke smoothness. These variables were chosen according to their perceived importance to maximal rowing and because they allow skill based variables to be used in conjunction with work output to achieve accurate discrimination between rowers and provide more meaningful feedback for rowers and their coaches.

The objective of competitive rowing is to cover a 2,000 metre rowing course in the shortest possible time. The force applied by the rower at each part of the stroke and the rower's rate of work output over the duration of the event are two major variables that affect the maintenance of boat velocity. While it is considered that the maintenance of a constant velocity throughout a race would be the most economical way to complete the set distance, rowers almost invariably adopt a pacing strategy where the velocity varies considerably.
The tactics of energy expenditure utilized by rowers result in power output decreasing progressively from the first to fourth minutes, levelling off between the third and fifth minutes and increasing to approximately third minute values during the final minute as the rower undertakes a finishing sprint. This "U" shaped pattern of power output indicates a lack of consistency in work output.

This pacing strategy appears to be based on traditional beliefs concerning race tactics and the desirability of being "ahead" (and thus being able to view the opposition) rather than on an understanding of the effects of velocity fluctuation on power output. That is, given the same average velocity, the power output required to row at varying velocities is greater than the power output required to row at a constant velocity.

Therefore, phase two of this study was designed to determine whether mean propulsive power output per kilogram of body mass could be significantly increased by a more constant pattern of power output as reflected in an increase in propulsive work consistency. Kinetic information feedback of individual force-angle profile characteristics compared to a criterion force-angle profile template was used to modify work output patterns during maximal ergometric rowing.

A central focus of this phase of the study was to examine the benefits to be derived from real-time kinetic information feedback during the performance of a multiple-degrees-of-freedom task.

## Delimitations of the study

This study was delimited to:

(1) Male rowers who had undertaken 6 minute maximal rowing ergometer tests at the Biomechanics Laboratory, Cumberland College of Health

Sciences. The subjects included 9 novice, 23 state, 9 national and 34 club level rowers.

(2) The investigation of selected biomechanical responses of male rowers of differing ability levels during a 6 minute maximal rowing ergometer test (phase one).

(3) An examination of the effects of kinetic information feedback on selected biomechanical responses of club level male rowers during a 6 minute maximal rowing ergometer test (phase two).

## Limitations of the study

The conclusions drawn from this study were limited by the following factors:

(1) The sample sizes, particularly for novice and elite rowers.

(2) Non-random selection of subjects.

(3) Variations in training status between groups of subjects.

(4) The validity and reliability of the instrumentation.

(5) Control of testing procedures.

(6) The extent to which the testing apparatus, that is the wheeled rowing ergometer, simulates the on-water (or in-boat) situation.

(7) The extent to which augmented concurrent visual feedback in the form of force-angle profile characteristics provides information regarding the maximal rowing task.

## Definition of terms

(1) Novice rowers. Adult rowers with less than 1 year of rowing experience.

(2) State level rowers. Adult rowers participating at or considered to be of a standard of rowing ability suitable for interstate competition.

(3) National level rowers. Adult rowers participating at international levels of competition.

(4) Club level rowers. Adult rowers with a minimum of 1 year of rowing experience participating at or considered to be of a standard of rowing ability suitable for 2nd to 4th grade competition (4th grade being the lowest level and 1st grade being the highest).

(5) Concurrent feedback. Feedback supplied while the performer is moving.

(6) Augmented feedback. Feedback in the form of special information not ordinarily present in a task; that is extrinsic to the individual and which supplements feedback obtained from the senses.

(7) Knowledge of performance. Augmented feedback concerning the movement pattern itself, that is, the temporal, spatial, sequential or force aspects of the movement.

(8) Knowledge of results. Verbal (or verbalizable), terminal, augmented feedback concerning the learner's success in achieving an intended goal.

(9) Kinetic information feedback. Augmented concurrent visual feedback in the form of continuous long persistence oscilloscope traces of performer generated force-angle profiles simultaneously comparable with a criterion force-angle profile template.

(10) Force-angle profile. A plot of the force applied by a rower on the oar handle as a function of the oar angle.

(11) Mean propulsive power output per kilogram of body mass. The average of the rower's power output over a 6 minute maximal rowing ergometer test.

(12) Propulsive work consistency. The uniformity of a rower's power ouput over a 6 minute maximal rowing ergometer test.

(13) Stroke-to-stroke consistency. A measure of the accuracy with which force and angle values are traced by a rower stroke after stroke, that is, the grand mean of the stroke-to-stroke consistencies obtained for 13, 8 second samples taken during a 6 minute maximal rowing ergometer test.

(14) Stroke smoothness. A measure of the nature of a rower's force application during the drive phase of a rowing stroke, determined by fourier transforms of averaged force data for a 6 minute maximal rowing ergometer test.

## Summary

The coaching education program adopted by the Australian Rowing Council as part of the National Coaching Accreditation Scheme requires neophyte coaches to consider many features of the human movement/sports science disciplines along with the technical and skill based aspects of competitive rowing. The degree to which these coaches are able to utilize this information to determine the demands of rowing and rower responses to these demands is not readily apparent.

Rowing is a unique human activity given that the body is supported by a moving seat and that both the legs and arms are involved with the legs working in the same phase. Boat motion occurs as a result of the manipulation of the oar(s) by the rower. For optimum rowing performance it is necessary for the rower to maximize concurrently both the forces generated and the effectiveness with which these forces are applied. In order to study these variables it is necessary to divide the rowing stroke into four component parts namely the catch, drive, finish, and recovery phases. The drive component represents 60% of the total stroke cycle, while the recovery component represents the first 20% and the last 10% of the cycle.

The extent to which the rower can influence the forward motion of the boat depends on the magnitude of the force applied to the oar and the distance (or angle) through which that force operates. A plot of this relationship, known as the force-angle profile allows examination of the force applied by the rower at each stage of the stroke during the drive phase.

The coaching and teaching of the rowing stroke has traditionally involved visual analysis of the relationships between the oar, the boat and the rower's body. It is arguable that visual analysis of what is happening between the rower, the oar and the water may not provide the coach with sufficient information to accurately quantify or analyze the stroke.

Sports biomechanics allows both quantitative and qualitative assessment of motor tasks. However, most coaches and teachers rely on experience, intuition and trial-and-error in effecting performance variation. Performance in a particular sport is related to a number of identifiable performance variables, each of a particular value to the task in question.

While there has been considerable research into the anthropometric and physiological parameters influencing rowing performance, there has been little research into the combination and relative importance of biomechanical performance variables in competitive rowing. Of particular importance in this study were those variables derived from oar force and oar angle data.

Competitive rowing is considered to be one of the most exacting of the continuous endurance sports requiring high levels of aerobic power combined with muscular strength and endurance. The anaerobic metabolism is believed to be primarily involved in the beginning (30 to

90 seconds) and finishing (30 to 60 seconds) sprints. The unique work output pattern adopted by rowers results in power output decreasing relative to blood lactate accumulation indicating a lack of consistency in work output.

As a motor skill, rowing requires the development of a highly consistent and efficient movement pattern. While ensuring a high level of movement consistency it is also important to ensure that the movement being practised is the most biomechanically efficient for the individual rower. The role of the coach is that of a movement diagnostician and prescriber who detects errors and varies movement patterns for increased proficiency. In order to adequately assist the rower through accurate error detection and correction, the coach must be able to understand and utilize objective information feedback related to rowing performance.

Apart from practice, information feedback is perhaps the most important determinant of motor skill acquisition. Information feedback is used to modify performance so that relevant motor behaviours can be acquired in respect of a specified movement objective. Many different aspects of a movement can be described and used as information feedback, the task being to determine what kinds of information are appropriate. Knowledge of results has long been considered the most potent form of information feedback in that it allows a performer to examine the outcome of an action in relation to a externally defined goal.

However, it is apparent that the performer is only informed of what happened relative to the outcome of the action. There is no information concerning how the action was completed which suggests that traditional knowledge of results may not provide the necessary information feedback for optimal performance.

A complete description of a movement pattern necessitates consideration of the kinematic (displacement, velocity and acceleration) or kinetic (mass, force and time) characteristics of the movement. While these characteristics are regularly determined in sports biomechanics research, their potential as information feedback, while often acknowledged, has received comparatively little research interest. There is growing support for the utilization of kinematic and kinetic variables as information feedback, the belief being that these variables can significantly influence the acquisition and optimization of motor skills.

For the purposes of this study a real-time force-angle profile measurement and analysis system was developed for maximal ergometric rowing. This system was designed to identify and enhance biomechanical performance variables of importance to maximal rowing.

This study aimed to identify a number of biomechanical performance variables derived from an analysis of force and oar angle data which could be used to accurately discriminate between rowers of differing ability levels and which would provide useful feedback for coaches and rowers. The biomechanical performace variables of interest included mean propulsive power output per kilogram of body mass, propulsive work consistency, stroke-to-stroke consistency and stroke smoothness. It was hypothesized that of these variables, propulsive work consistency would be the least effective discriminator between groups of rowers.

This study also aimed to determine the effects of kinetic information feedback on propulsive work consistency and mean propulsive power output per kilogram of body mass during maximal ergometric rowing. It was hypothesized that kinetic information feedback of stroke-to-stroke force-angle profile characteristics compared to a criterion force-angle profile template would significantly improve propulsive work consistency. It was also hypothesized that a more constant pattern of power output, reflected in a significant increase in propulsive work consistency, would result in a significantly higher mean propulsive power output per kilogram of body mass obtained during maximal ergometric rowing.

# Chapter 2

# REVIEW OF LITERATURE

## Introduction

Rowing is a particularly ancient form of human transport. Archaeological remains from the 5th Dynasty of the Pharoahs (c2600BC) show the use of long oars for boat propulsion in ancient Egypt. The traditional technique of rowing may be traced back to the Roman conquest and to contests organized by Emperors Augustus and Claudius (Dal Monte and Komor, 1988; Foley and Soedel, 1981), however, competitive rowing, as it is currently recognized, has evolved since the Napoleonic wars. The sport was established in the English Public Schools in the early 1700's and then spread to the universities with the annual Boat Race between Oxford and Cambridge Universities commencing in 1829. About the same time, several Thames-based metropolitan clubs were established (Edwards, 1963; Pannell, 1972). Rowing became an Olympic sport at the Paris Olympic Games of 1900 and during the succeeding decades has undergone a number of changes and developments particularly in the materials and designs used for oar and boat construction and the use of new ideas such as the sliding seat, which have enabled rowers to perform more efficiently (Dal Monte and Komor, 1988). An interesting account of the history of rowing, in particular, the history of Australian rowing, has been provided by Jacobsen (1984).

The development of the modern racing boat and rowing technique has occurred by gradual evolution with innovation often being resisted in the conservative milieu that tends to characterize competitive rowing. The earliest considerations of the biomechanics of rowing were conducted at the end of the 19th and the beginning of the 20th centuries. These studies focused on measurement of the forces applied to the oar and an early assessment of the efficiency of the rowing movement (Dal Monte and Komor, 1988). While the early research into the biomechanics of rowing concentrated on the kinematic and dynamic characteristics of the boat-oar-rower relationship, more recent studies have addressed the effects of a variety of limiting factors on rowing performance and have also attempted to objectively evaluate individual rowing technique. Other research has sought to examine the role of biomechanical information in crew selection as well as the effects of hydrodynamic influences and the development of boat and oar equipment. The most recent research has centred around advances in the computing and technology areas with studies dealing with mathematical modelling, computer simulation of the rowing action, and the development and application of sophisticated computerized measurement systems (Dal Monte and Komor, 1988).

At this point in time, there appears to be scant information concerning the use of biomechanical data for discrimination purposes in competitive rowing. The same situation exists concerning the use of biomechanical information as concurrent augmented feedback in order to enhance rowing performance. However, the use of biomechanical variables as feedback items for motor skill learning and performance is receiving increased attention from researchers.

The following review of the literature examines biomechanical analysis, oar force measurement and analysis, work capacity and multivariate analysis in rowing, as well as the use of augmented information feedback for the modification of motor performance and the efficacy of visual feedback in motor behaviour.

## Biomechanical analysis in rowing

Analysis of the biomechanics of rowing has largely been concerned with descriptions of the interactions between rower, oar and boat (Angst and Fischer, 1985; Angst, Gerber and Stussi, 1985; Bompa, Hebbelinck and Van Gheluwe, 1985; Ishiko, 1971; McMahon, 1971; Martin and Bernfield, 1980; Martindale and Robertson, 1984; Munro, 1979; Pannel, 1972, 1979; Sanderson and Martindale, 1986; Wellicome, 1967; Williams, 1967), or analytical procedures for the assessment of rowing capacity and skill (Angst, 1980, 1984; Christov, Christov and Zdravkov, 1988; Gerber, Jenny, Sudan and Stussi, 1985; Komor and Leonardi, 1988; Leighton, 1983; Nelson and Widule, 1983; Schneider, 1979; Smith, Camden and Stuckey, 1987; Smith, Spinks and Moncrieff, 1988). Comparative research has centred around kinematic analysis of rowing efficiency (Nelson and Widule, 1983), bladework (angle and velocity), and boat velocity (Donoghoe, 1985; Marr and Stafford, 1983).

## Analysis of the rowing stroke

The essential ingredients of successful rowing were seen by Edwards (1963, p.20) as being related to "oarsmanship", "crewmanship", "fitmanship", and "morale". In examining the concepts of "oarsmanship" and "crewmanship" the author undertook what was in essence, a rudimentary examination of the biomechanics of rowing. An understanding of the mechanical principles concerned with moving a boat was believed to be helpful in determining the causes of inefficient rowing. Study of the mechanical principles of rowing was deemed necessary, if objective assessments were to be made regarding potential improvements to rowing equipment. Assessment of the motive power of the rower and the interaction between the rower and the boat was believed to be concerned with the "art" of oarsmanship, with the aim being to improve the effectiveness of the rower.

The mechanical principles associated with "oarsmanship" included the leverage system created by the interaction of the oar with the water, the forces acting on the oar, the turning point of the oar and the ratio of stroke to run (the rhythm of the drive phase of the rowing stroke to the run of the boat during the recovery phase). Oar-mounted accelerometer and strain gauge recordings were utilized along with slow motion film, taken from an overhead bridge, to assess the distance travelled during the stroke, the stroke to run ratio, and to analyze the stroke itself as well as the behaviour of the blade in the water.

The recorded data indicated that the distance covered during the stroke was some 2.6 metres greater than previously estimated and that the ratio of stroke to run was closer to 1:1.7 rather than the accepted 1:2.4 depending on the nature of the stroke and the stroke rate.

These readings prompted Edwards to cast considerable doubt on previously accepted mechanical characteristics of the rowing technique of the "ideal" rower and to consider alterations to the catch, the stroke angle and oar length in an attempt to improve rowing efficiency. Unfortunately, the analysis of the "art" of rowing was purely descriptive wherein Edwards failed to utilize biomechanical information to support the claim that "the traditional English style when properly performed is the best, as it enables the oarsman to apply the maximum power for the least waste of energy" (Edwards, 1963, p.48). However, an examination of the influence of the five main muscle groups used in propelling the boat proved to be an interesting kinesiological analysis of the rowing effort.

In examining the concept of "crewmanship", Edwards dealt with the application of the art of rowing to the efficient propulsion of the boat. In considering the processes required to make the rower as efficient as possible both as an individual and as a crew-member, the author proposed that the rower was more important than the rig or differences in boats and oars. Therefore, the information related to "crewmanship" was considered in light of the interaction between the rower and boat, rig and oar designs. Once again, a descriptive analysis of the rowing stroke was used along with consideration of such rigging variables as the height of the work, the length of the slide, the length of the stroke, oar length, and the shape of the oar blade.

While a particularly detailed account, and a useful precursor to the biomechanical analysis of rowing, Edwards' descriptions of "oarsmanship" and "crewmanship" were largely based on the author's observations of the rower's stroke technique whilst interacting with the host of variables mentioned above. Edwards (1963, p.61) saw the effective stroke as being characterized by the following features:

1. Body swing forward from the thigh joints.
2. Back straight, chin up.
3. Oar handle at a constant height.
4. Oar held lightly in fingers, wrists flat.
5. Outside shoulder articulating forwards.
6. Rolling the oar, outside fingers flexed.
7. Shins vertical, ribs close to thighs.
8. Spring; outside fingers hooked round oar.
9. Phasing of body and slide. Arms straight.
10. Shoulders still not drawn back.
11. Body vertical, 2 inches of slide, shoulders, back, arms.
12. 20 degrees of swing.
13. Inside wrist arching, outside forearm horizontal.
14. Unrolling round the turn.

15. Hands away at constant speed.
16. Smooth recovery.

Thus, rowing style dictated the author's perceptions of rowing efficiency.

A clearer biomechanical perspective of rowing was provided by Williams (1967) who saw the behaviour of the rower's body as being representative of a transmission system (as distinct from a power source). Style was seen as being largely constant due to the nature of the propulsive system. The limitations on style were believed to be anatomical (including joint flexibility and anthropometric ratios) and physiological. The actions carried out by the rower were considered in terms of the extent to which propulsive force was applied to the boat. It was proposed that the rower's contribution to boat propulsion may be improved by increasing total energy expenditure and/or by reducing extraneous energy expenditure and/or by restricting those actions likely to impede the run of the boat. The argument followed, that care must be taken when eliminating so-called style "errors", prior to an assessment of the manner in which the rower compensates for these "errors", and the overall effect of these perceived faults on the run of the boat.

The biomechanical factors considered by Williams (1967) were those features of the rowing action where some clarification of thought was deemed necessary, particularly as these factors were believed to influence the timing, sequencing and the pattern of the rower's body movements. The influence of the oar on the rower was considered because the path of the oar handle and its general spatial relationships were seen as being fundamental to the rower's movement pattern. The biomechanical principle concerning the horizontal path of the oar handle that emerged from this consideration, was that the blade of the oar must be accelerated to the speed of the water prior to engaging the water at the catch, while at the finish of the stroke the blade must be extracted when it is stationary relative to the water. The interaction between the boat and the rower was described as a binary system wherein the path of the centre of gravity of the system depends upon the movement of the centre of gravity of each of the component parts that is, boat and crew, and the interaction between the system that is, boat plus crew, and the environment. An understanding of the binary nature of boat plus crew was seen as being of importance in the consideration of sliding technique and in particular, the relationship between the length of body swing and the angle through which the oar travels.

The importance of progressive power output as a means of overcoming increased resistance resulting from increased boat acceleration was also considered due to the deleterious effects of decreased acceleration on the movement of the oar handle as well as the rower's sequence of movement. Oar slip and whip in the oar loom were believed to decrease progressive power output by dissipating energy. Awareness of biomechanical constants such as the length of the body swing and an understanding of the effects of non-perpendicular oar movement on oar rotation speed were seen as being necessary for rig construction.

The optimum catch position from a mechanical viewpoint was described as one where the knees are not allowed to flex below 90 degrees and where the lumbar and cervical spines are held firm. The extent to which the rower approaches 90 degrees was seen as being related to the freedom of movement required to place the blade in the water. Having achieved an effective catch, progressive power output was seen as bringing the rower to the finish position with an extended trunk at or slightly past the vertical, the legs down with the knees extended, a thigh/trunk angle between 100 and 120 degrees and with the hands some 2.25 to 3.0 centimetres from the trunk. This finish position was believed to facilitate disengagement of the oar blade.

The approach taken by Williams is worthy of the relatively close examination accorded it here as the author did not set out to describe the rowing action or to propose a particular rowing style. Instead, an attempt was made to examine those biomechanical factors that influence the "personal performance potential" (Williams, 1967, p.81) of individual rowers and in doing so, the author challenged the concept of observed (style-based) rowing "faults" believing that faults in any rower exist only when they adversely affect crew performance.

Pannell (1972) also doubted the wisdom of concentrating on any single aspect of the rowing stroke and was critical of the practice of imitating particular methods or styles of rowing. The author stated that with a reasonable understanding of kinesiology and of basic mechanical principles, that the individual coach could appreciate the fundamental aspects of the rowing stroke. In describing the mechanics of oar, boat and body, Pannell (1979) stated that the rower's body actions in the boat must act in conjunction with the movements of the oar in order to provide the most efficient propulsion of the boat (see Figure 4). Thus the author was concerned with leverage, acceleration and retardation of the boat, the mechanics of the rowing stroke, the velocity curve of the boat, the angle through which the oar is rowed, the velocity of the oar handle, the movements of the body during the finish of the stroke, the move forward, the full forward position, and the reverse movement.

### Kinematics of rowing

Following on from the work of Edwards (1963), Williams (1967), and Pannell (1972; 1979), a number of studies have been conducted to examine the kinematic characteristics of rowing. As explained by Munro (1979) kinematics is that branch of biomechanics used to describe motion. An analysis of basic kinematic concepts such as rating frequencies, displacements, velocities and accelerations can be utilized to provide the rowing coach with valuable information regarding rowing performance.

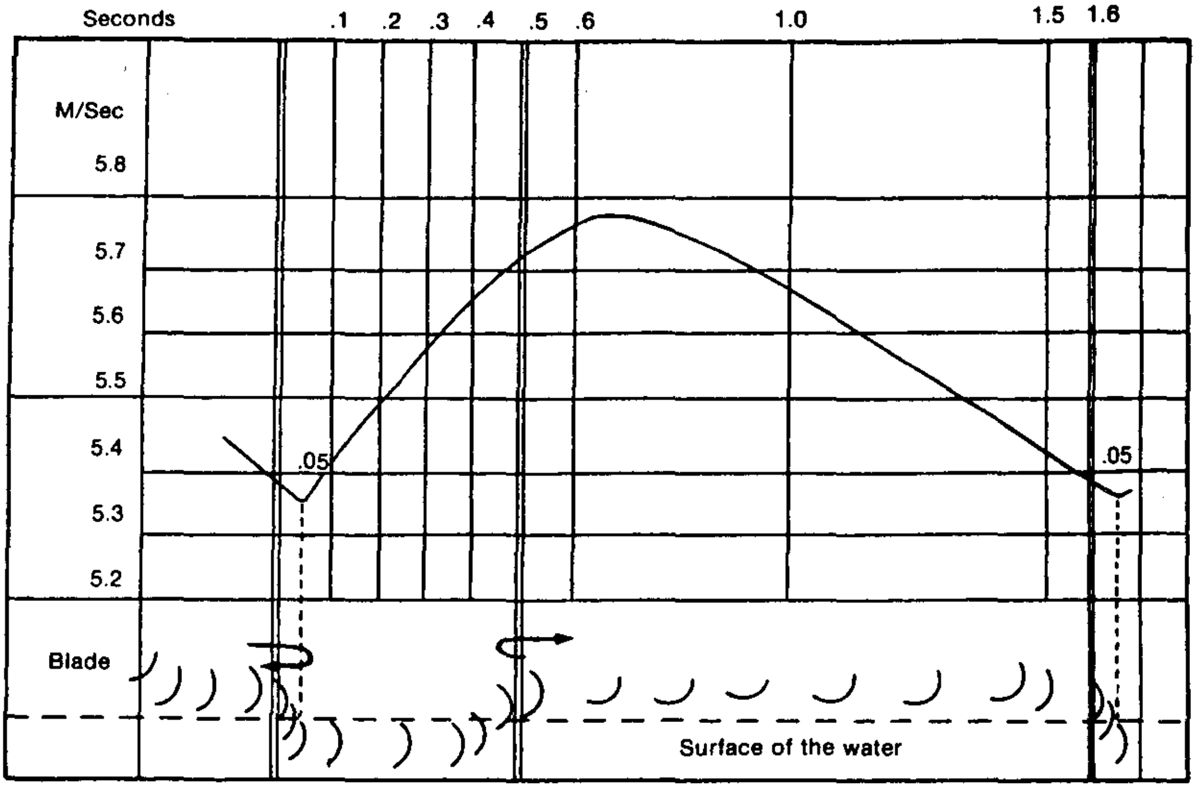


**Figure 4** Velocity of the boat during the rowing stroke (Pannel, 1980, p.17)

The extent to which rowing coaches related rowing technique to the aesthetic appearance of the rowing action rather than to the level of efficiency was of particular concern to Bompa (1980), who believed that the teaching of rowing technique should take into account basic kinesiological and biomechanical concepts when attempting to improve muscular efficiency. Maximal isometric strength of 18 rowers was tested in three facets of the rowing stroke namely, the height of the sagittal pull, the angle of pull in the sagittal plane and the power position at the catch and the finish of the stroke. It was determined that the most effective height for the sagittal pull occurs at the level of the umbilicus and that a 180 degree extension of the elbow produces greater force than when the elbow is slightly flexed. As suggested by Edwards (1963), the "elbow out" finish position was found to be inefficient due to restricted movement of the m. Latissimus dorsi. Bompa proposed that coaches consider these biomechanical factors when developing rowing technique.

The most important determinant of rowing performance was seen by Martin and Bernfield (1980) as being the average velocity of the boat which in turn, was the product of stroke length and stroke frequency. It was apparent to the authors that both of these variables were influenced by rowing technique and the nature of the rig, and that there was little empirical data that could be used to quantify rowing styles. Therefore, the researchers set out to examine, via cinematographic analysis, the effect of stroke rates of 37, 39 and 41 strokes per minute on the pattern and amplitude of the velocity-time curve of the boat, to quantify the movement components of a stroke cycle representative of a successful rowing style (Rosenberg technique) and to analyze the influence of stroke rate on the component parts of the rowing stroke.

It was determined that while the times for the components of the stroke cycle changed, the pattern of the velocity-time curve did not vary when the stroke rate was increased. Also the stroke rate had little effect on the location of the minimum and maximum velocity-time curve values. Minimum boat velocity occurred at approximately 27% of the leg drive (pull) phase of the stroke cycle. This phenomena was explained in terms of the time taken to produce enough force to overcome water resistance, the fact that the oar blades must be moving at a greater velocity than the water flowing past the boat before adequate force can be generated to affect boat acceleration, and that some of the force produced is used to accelerate the mass of the rower in relation to the boat. Maximum boat velocity was apparent in the middle of the seat movement (or recovery) phase.

The average velocity-time curve amplitude was 2.70 metres per second which indicated a considerable variation in velocity during the stroke cycle. Given that drag on a boat is approximately proportional to the square of its velocity, the authors hypothesized that a boat could be rowed at a higher average velocity if the amplitude of the boat velocity-time curve could be reduced. This hypothesis was not supported as increased stroke rate did not result in reduced amplitude of the velocity-time curve.

In analyzing the amplitude data, Martin and Bernfield found that the average minimum boat velocity varied minus 24.4% from the mean velocity while the average maximum velocity deviated by plus 18.6%. This finding was explained in terms of the drag forces on the boat resulting in the boat being easier to accelerate when it was moving at a relatively slow velocity. Therefore, the smaller variation of the maximum velocity from the mean velocity was believed to be the result of drag forces and/or limited energy in the moving mass. Furthermore, a significant positive relationship ($r$=.66, $p$<.05) was found between average velocity and stroke rate. Overall analysis of the stroke cycle indicated that increased boat velocity was achieved by increased force application during the drive phase and the application of force over an increased percentage of the stroke cycle time.

As stated previously, information about the biomechanics of rowing is scarce in the scientific literature. Wilson et al. (1988) reported that much of the completed research focused on quantification of the external forces generated by the rower with little research having been conducted on the nature and location of the forces produced by the individual rower.

Comparative electromyographic analyses of rowers were first conducted by Daireaux and Pottier (1983) who found that experienced rowers produced greater m. Vastus lateralis and lesser m. Biceps femoris integrated electromyographic signals throughout the complete rowing cycle when compared to novice rowers. Novice rowers were also found to have a greater variation in electromyographic signals of the m. Biceps brachii, wrist flexors, wrist extensors, m. Rhomboids, m. Trapezius, m. Erector spinae, and m. Vastus lateralis. This variance along with elevated m. Vastus lateralis activity during the recovery phase was believed to be due to eccentric contraction resulting from braking requirements due to the adoption of fast, gliding movements during the recovery phase of the rowing cycle (Wilson et al. 1988).

Videography and electromyography were used by Marr and Stafford (1982) to examine the differences in technique demonstrated by an experienced junior and a novice rower during a 20 stroke maximal rowing ergometer effort. Electromyographic traces of the hamstrings, m. Erector spinae and m. Latissimus dorsi were analyzed for the length of contraction, the timing of contraction relative to the rowing action and the intensity of contraction. The experienced junior had a greater average oar handle displacement and velocity per stroke, better summation of joint forces and a more efficient pattern of movement during the recovery phase. The electromyographic analysis indicated that the muscle groups of the experienced junior rower were active for a longer period of time and contracted at a greater intensity. than those of the novice rower.

Robertson (1985) utilized electromyographic analysis in an attempt to determine the most efficient rowing technique. This study aimed to examine whether rowers used reciprocal inhibition of antagonistic muscles in order to diminish energy expenditure during the rowing stroke. The two female rowers who participated in this study did not demonstrate reciprocal inhibition of the leg muscles, however, several antagonists were found to act in a synergistic fashion. For example, two knee flexors, m. Biceps femoris and m. Gastrocnemius were maximally recruited along with the knee extensors, m. Vastus lateralis and m. Vastus medialis. Also, two antagonistic hip muscles, m. Gluteus maximus and m. Rectus femoris acted synchronously during the drive phase, however, full recruitment of the m. Rectus femoris did not occur.

Wilson et al. (1988) extended the above study utilizing a larger sample of male rowers (N=9). It was determined that the m. Gluteus maximus, m. Biceps femoris, m. Rectus femoris, m. Vastus lateralis, m. Gastrocnemius, and m. Tibialis anterior were all activated at or just prior to the beginning of the stroke and reached maximal activation near the application of peak force. Coactivation of the m. Vastus lateralis, m. Rectus femoris, m. Gluteus maximus, m. Biceps femoris, and m. Gastrocnemius occurred despite the antagonistic relationship between the knee flexors, m. Biceps femoris and m. Gastrocnemius and the knee extensors, m. Vastus lateralis and m. Rectus femoris. This finding was explained according to Lombard's paradox wherein all of these muscles are known to act as extensors of the knee. The m. Gastrocnemius was found to act both as a knee extensor and as a plantar flexor. Knee extension was also believed to be produced by the action of the m. Gluteus maximus about the rigid link created by the m. Rectus femoris between the pelvis and tibia. The recovery phase of the rowing stroke involved dorsiflexion and hip flexion produced in part by m. Tibialis anterior and m. Rectus femoris, respectively. It was also determined that m. Vastus lateralis acts eccentrically in knee flexion inhibition and muscle preloading during the latter stages of recovery.

A study conducted by Nelson and Widule (1983) set out to determine how the actions of the rower relate to the movement of the oar, in particular, which components of the body instigate the drive, and how the movements of the components are related. Cinematographical techniques were used to analyze the kinematic characteristics of novice ($\underline{n}$=8) and skilled female ($\underline{n}$=10) rowers during eight 1 minute efforts on a rowing ergometer. The skilled rowers were shown to have a higher horizontal ~~linear~~ oar velocity than the novice rowers when the oar was perpendicular to the line of action. A more rapid extension of the knee during the drive phase was seen as the main reason for this difference. However, a contributing factor was the higher sum of trunk and angular knee velocity for the skilled rowers at the time when the oar was perpendicular to the line of action. The skilled rowers demonstrated a lower time differential between the occurrence of maximum angular velocity of the knee and trunk. There was an 11% difference ~~in efficiency~~ between the novice and skilled rowers based on the ratio of actual to possible sum of knee and trunk angular velocity. This difference was seen as accounting for a large part of the 19% variation between the novice and skilled rowers in terms of the mean horizontal ~~linear~~ oar velocity at the "square-off" position.

Martindale and Robertson (1984) quantified and contrasted the instantaneous segmental and total body mechanical energy patterns of rowing both a single scull and a rowing ergometer. Energy savings through the exchange of mechanical energy among body segments and conversion of energy within body segments were also contrasted. Two male and two female scullers were filmed at "low", "medium" and "high" stroke rates while rowing on a stationary rowing ergometer, a wheeled rowing ergometer and a single scull racing boat. Internal work measures were highest in the single scull and lowest in the wheeled rowing ergometer while energy conservation through exchanges among body segments was greatest in the single scull and least in the stationary rowing ergometer. Energy conservation through inter-conversion (expressed as a percentage of total work) was greatest in the wheeled rowing ergometer while being comparable for both the single scull and the stationary rowing ergometer. The authors called for further examination of power application in rowing including measurement of the forces applied at the oar lock, oar and/or stretcher.

Bompa et al. (1985) pointed out that while force is generated by the legs, the upper body and the arms during the rowing stroke, it is the arms which directly convey force to the oar. The force output of the arms was believed to be a function of the forearm position used by the rower whilst gripping the oar. It was hypothesized that a mixed grip (one arm prone, the other semiprone) would be mechanically superior to the traditional pronated forearm grip. It was determined that the mixed grip produced a significantly higher force output than the prone grip. The superiority of the mixed grip was believed to be due to more effective utilization of the elbow flexors, namely m. Biceps brachii, m. Brachialis, m. Brachioradialis, and m. Pronator teres. It was pointed out that during rotation of the forearm from supination to pronation only the m. Brachialis remains unaffected whilst the other three muscles change their length, their mechanical leverage, and therefore, their efficiency. Forearm rotation from the semiprone to prone position, as in the mixed grip, was believed to influence only the m. Biceps brachii by reducing its mechanical advantage and therefore the effective lever arm.

As well as the above factors, the use of the modified handle developed by Bompa et al. (1985) for this study, enabled the upper arm to move backwards past the frontal plane of the upper body resulting in full upper arm extension. This allowed a greater contribution from the m. Lattismus dorsi and thus a higher force output from the rower.

Despite these encouraging findings and the apparent legality of the modified oar handle, the current author is not aware of any attempts to utilize the mixed grip in competitive rowing. This situation may be due to limitations in the experimental protocol and instrumentation utilized by the authors. For example, data collection was restricted to a short series of strokes (two sets of five) at a restricted and relatively low stroke rate (24-26 strokes per minute). Also, the instrumentation utilized did not allow for accurate stroke-to-stroke assessment of oar force and there is some doubt (Leighton, 1983) whether the strain gauge technique utilized in this study was effective in isolating the forces in question.

A biomechanical analysis of blade work and boat movement for a novice and an experienced double scull crew was undertaken by Donoghoe (1985). Cinematographical analysis utilizing both overhead and side-on filming positions was used to compare both crews in terms of the phases of the rowing cycle, the blade angles throughout the stroke, the angular velocity of the blades, and the boat velocity. The experienced crew accomplished the rowing cycle with more precise timing and more efficient blade movement at the catch and the finish than the novice crew. The more efficient blade manipulation of the experienced crew resulted in a higher boat velocity during the recovery phase than that generated by the novice crew.

An equation to describe the speed of a rowing boat as a function of the movement of a sculler's centre of mass relative to the boat and the force applied was developed and solved by Sanderson and Martindale (1986). The authors proposed a method to determine the degree to which variations in boat speed during the rowing cycle influence the amount of power necessary to move a rowing boat at a pre-determined mean speed. Technique changes were proposed as a way of minimizing the effects of boat speed variation and of maximizing mean speed for a given quantity of propulsive power. For example, the importance of a quick catch and a smooth recovery was stressed. It was also determined that the ratio of the power utilized in boat propulsion to the power dissipated through water movement in the oar "puddle" (or oar "slip") indicated that the use of a larger blade area would serve to increase propulsive efficiency.

A similarity analysis was undertaken to determine if larger rowers had an advantage over smaller rowers in race situations. The analysis suggested that boat mass should be made proportional to the mass of the sculler if the smaller sculler was not to be put at a disadvantage. Even with such scaling of boat mass, the smaller rowers were still seen as being at a slight disadvantage due to the dependence of the drag coefficient on the scale of the boat.

The authors developed an equation to show how stroke rate should scale body mass for geometrically similar rowers thus allowing smaller rowers to adopt a stroke rate higher than larger rowers without any increased difficulty. Dimensional analysis was used to indicate how the ratio of internal power to propulsive power depends on stroke rate, stroke length and force applied to the oar.

The mechanical efficiency of five university oarsmen was determined by Fukunaga et al. (1986). The oarsmen were tested whilst rowing in a rowing tank with a water circulation rate of 3 metres per second. The subjects undertook a stepwise incremental work loading wherein the work intensity was increased by 10% of the pre-determined maximum force applied to the oarlock pin, every 2 minutes. It was determined that the increment in mechanical power was caused mainly by an increase in the mean force applied to the oarlock pin and was independent of the displacement of the oar handgrip. This result was in agreement with Di Prampero et al. (1971) who found that handgrip displacement was constant at varying stroke rates while the average pull and the work done per stroke increased with increasing stroke frequency. The increment in mechanical efficiency due to increased mean force application and stroke frequency was consistent with previous studies conducted by Gaesser and Brooks (1975), who found that the efficiency of bicycle ergometer exercise was increased by increasing the work rate, and Di Prampero et al. (1971) who found that the efficiency of rowing increased with stroke frequency.

Fukunaga et al. (1986) found that gross efficiency in rowing increased with force application at lower work intensities. In the mechanical work range of 124 to 182 watts, mechanical efficiency was almost constant at 17.5%. Net efficiency was 19.8% (±1.4%), work efficiency 27.5% (±2.9%) and delta efficiency 22.8% (±2.2%). These results differ somewhat from the mechanical efficiency values for rowing determined by Asami, Adachi and Yamamoto (1981) (16.2 ± 1.6%), Cunningham, Goode and Critz (1975) (18.1 ± 1.9%), Di Prampero et al. (1971) (18-23%) and Hagerman et al. (1978) (14%). Fukunaga et al. (1986) stated that the variations in the reported values could be explained by the use of different measurement techniques as well as different methods of calculating efficiency.

The ratio of the mechanical power of the oar to the progressive power of the boat was seen by Matsuo, Fukunaga and Yamamoto (1988) as an index of rowing skill. It was determined that a significant linear relationship ($\underline{r}=-0.87$, $\underline{p}<.01$) existed between the ratio and performance time indicating that elite rowing crews are able to skillfully translate power from the blade of the oar to the boat.

It is apparent therefore, that early work on the biomechanics of rowing involved preliminary evaluation of the efficiency of the rowing motion and measurement of the basic kinematic parameters of rowing. Objective assessment of the forces applied to the oar has also been a focus point in biomechanics research in rowing. The relationships between these forces and other biomechanical factors which determine final race time are of central importance to this study.

## Oar force measurement and analysis in rowing

The objective of competitive rowing is to propel the boat as quickly as possible over the race distance of 2,000 metres. A large number of related factors serve to influence the final time for a given race. In the first instance, final time depends upon the average velocity of the boat for the race distance as determined by the mean number of strokes for the total distance. Single stroke velocity is a function of the distance covered by one stroke and the stroke rate. The stroke distance is essentially of two parts, the pull distance (when the blade of the oar is in the water) and the recovery distance (when the blade of the oar is out of the water). The recovery distance is determined by the effects of air resistance on the rower, the oar and that part of the boat above the water line; hydrodynamic drag on that part of the boat below the water line; the mass of the boat-crew system and the time of the recovery phase. The pull distance is determined by the force applied by the rower on the oar handle, the hydrodynamic characteristics of the oar blade and the resulting force on the oar blade; the angular range of displacement of the oar from catch to finish; the time of the pull phase; the effects of air resistance on the rower, the oar and that part of the boat above the water line and hydrodynamic drag on that part of the boat below the water line (Dal

Monte and Komor, 1988). Figure 5 indicates the relationships between the biomechanical factors which determine final race time in rowing.

## Forces acting on the boat, oar, and rower

The forces acting on the complex boat-oar-rower mechanical system was described by Dal Monte and Komor (1988, pp.70-73) and are outlined in Figures 6-10. In order to simplify the description of the forces acting on the boat-oar-rower mechanical system, the authors utilized an analysis of the single-scull boat, stating that the equations and conclusions were valid for the other boat categories. The main forces acting on the boat-oar-rower mechanical system are shown in Figure 6 and may be described by the following equations:

$$\begin{aligned} F_X &= F_{bx} - D_t - m_t\ddot{X} &= 0 \\ F_Y &= F_{byz} - F_{byl} - m_t\ddot{Y} &= 0 \\ F_Z &= F_u + F_{bz} - m_t(g-\ddot{Z}) &= 0 \end{aligned} \qquad (1)$$

where $F_X$ = sum of the longitudinal forces acting on the system, $F_{bx}$ = longitudinal force acting on the oar blade, $D_t$ = total hydrodynamic drag, $M_t\ddot{X}$ = longitudinal acceleration of the total mass of the system, $F_Y$ = sum of the transverse forces acting on the oar blade, $F_{byl,2}$ = transverse forces acting on the oar blade, $M_t\ddot{Y}$ = transverse acceleration of the mass of the system, $F_Z$ = sum of vertical forces acting on the system, $F_u$ = upward lift force, $F_{bz}$ = vertical forces acting on the oar blade, $M_t(g-\ddot{Z})$ = vertical acceleration of the mass of the total system.

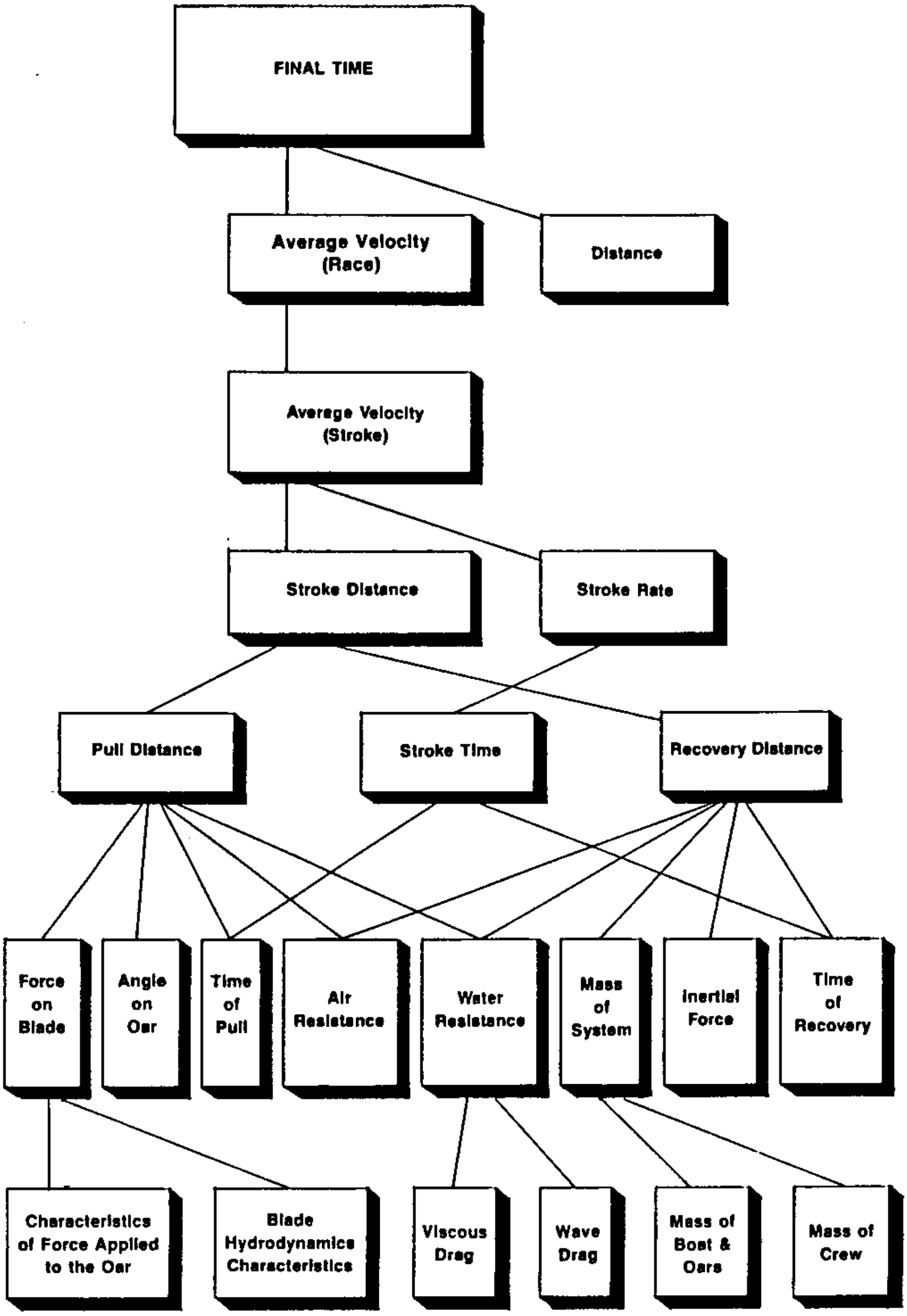


Figure 5 Biomechanical factors which determine final race time in rowing (Adapted from Schneider, 1981)

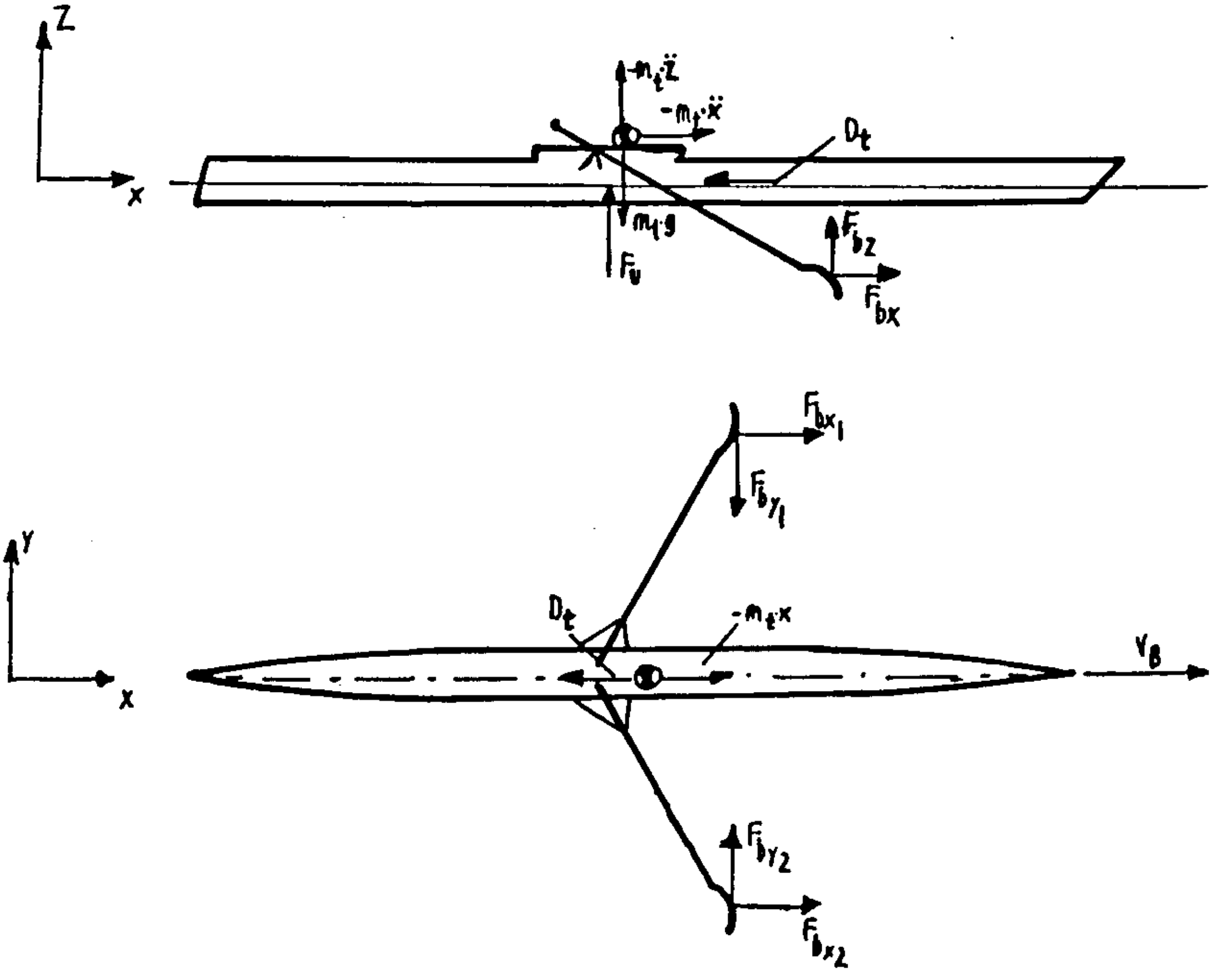


**Figure 6** The main forces acting on the boat-oar-rower mechanical system (Dal Monte and Komor, 1988, p.70)

The above expressions describe the pull phase of the stroke, that is, when $F_{bx} \neq 0$, $F_{by} \neq 0$, $F_{bz} \neq 0$. The recovery phase of the stroke may be described as follows:

$$
\begin{aligned}
F_X &= -D_t - m_t\ddot{X} &&= 0 \\
F_Y & &&= 0 \\
F_Z &= F_u - m_t(g-\ddot{Z}) &&= 0
\end{aligned}
\qquad (2)
$$

The forces acting on the boat are indicated in Figure 7 and may be described by the following equations:

$$
\begin{aligned}
F_X &= F_{OX} - F_{SX} + m_B\ddot{X} - D_t &&= 0 \\
F_Z &= F_u - F_{OZ} - F_{RS} - F_{SZ} + m_B(\ddot{Z}-g) &&= 0
\end{aligned}
\qquad (3)
$$

where, $F_{OX}$ = longitudinal reaction force on the oarlock, $F_{SX}$ = longitudinal reaction force on the foot stretcher, $m_B\ddot{X}$ = longitudinal acceleration of the mass of the boat, $F_{OZ}$ = transverse reaction force on the oarlock, $F_{RS}$ = reaction force on the seat, $m_B(\ddot{Z}-g)$ = vertical acceleration of the mass of the boat.

Figure 8 indicates the forces acting on the rower. Equation 4 describes the nature of these forces.

$$
\begin{aligned}
F_X &= F_{SX} - F_{hX} + m_C\ddot{X} &&= 0 \\
F_Y &= F_{SZ} - F_{hz} - m_C(g+\ddot{Z}) + F_{RS} &&= 0
\end{aligned}
\qquad (4)
$$

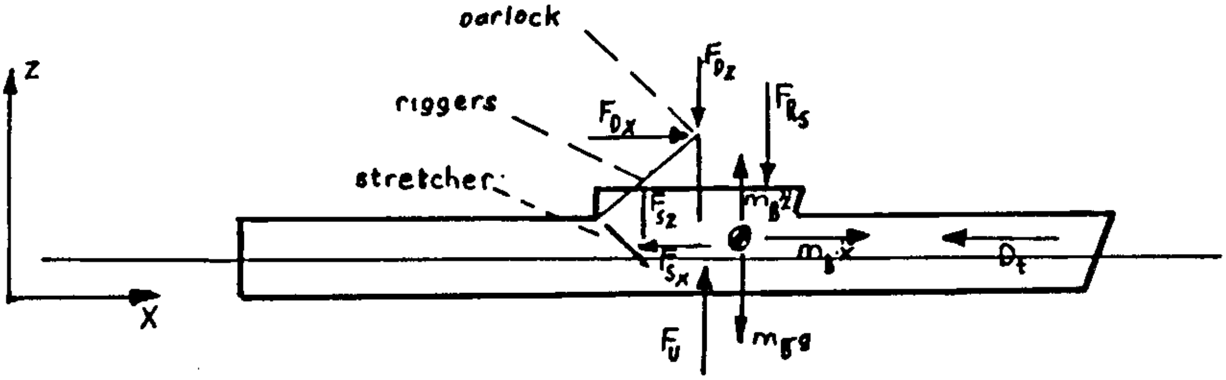


Figure 7 The main forces acting on the boat (Dal Monte and Komor, 1988, p.71)

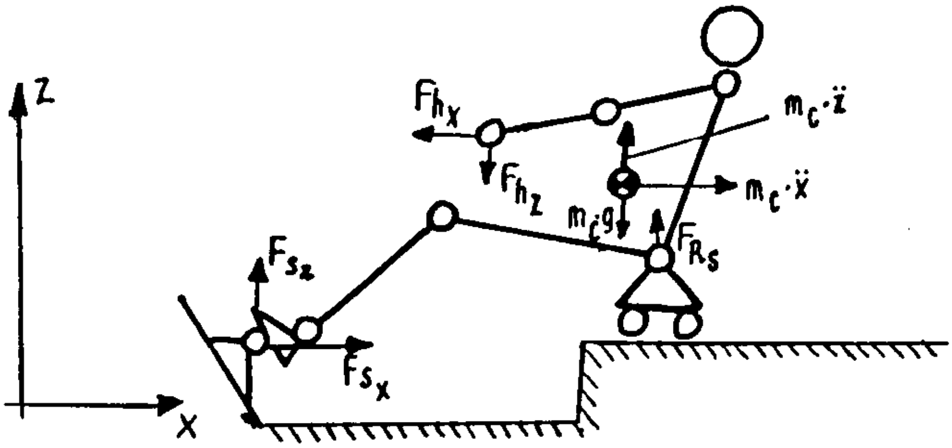


Figure 8 The forces acting on the rower (Dal Monte and Komor, 1988, p.71)

where, $F_{hX}$ = longitudinal force exerted on the oar handle, $m_c\ddot{X}$ = longitudinal acceleration of the rower's centre of mass, $F_{hZ}$ = vertical force exerted on the oar handle, $m_c(g+\ddot{Z})$ = vertical acceleration of the rower's centre of mass.

The forces acting on the oar and the oar blade are indicated in Figures 9 and 10 respectively. The components of these force are represented by the following expressions:

$$\begin{aligned} F_b &= F_p \sin\gamma \\ F_d &= F_b \cos\gamma \\ F_{bn} &= F_b \cos\epsilon' \\ F_{bn} &= F_b \sin\epsilon' \\ F_{bx} &= F_b \sin\psi \end{aligned} \tag{5}$$

where $Y$ = **arc tan** $(F_p/F_d)$ and results from blade propulsion $(S_p)$ and drag $(S_d)$ coefficients.

$$\epsilon' = \epsilon - 90^\circ$$

$$\epsilon = \text{arc tan } (F_p/F_d) + \alpha_f - \tau$$

$\alpha_f$ = **angular position of the oar blade**

$\tau$ = **angle between the longitudinal axes of the blade and the oar shaft**

The forces acting on the oar include:

(1) The reaction force between the oar blade and the water. This force has two components with the first acting in the same

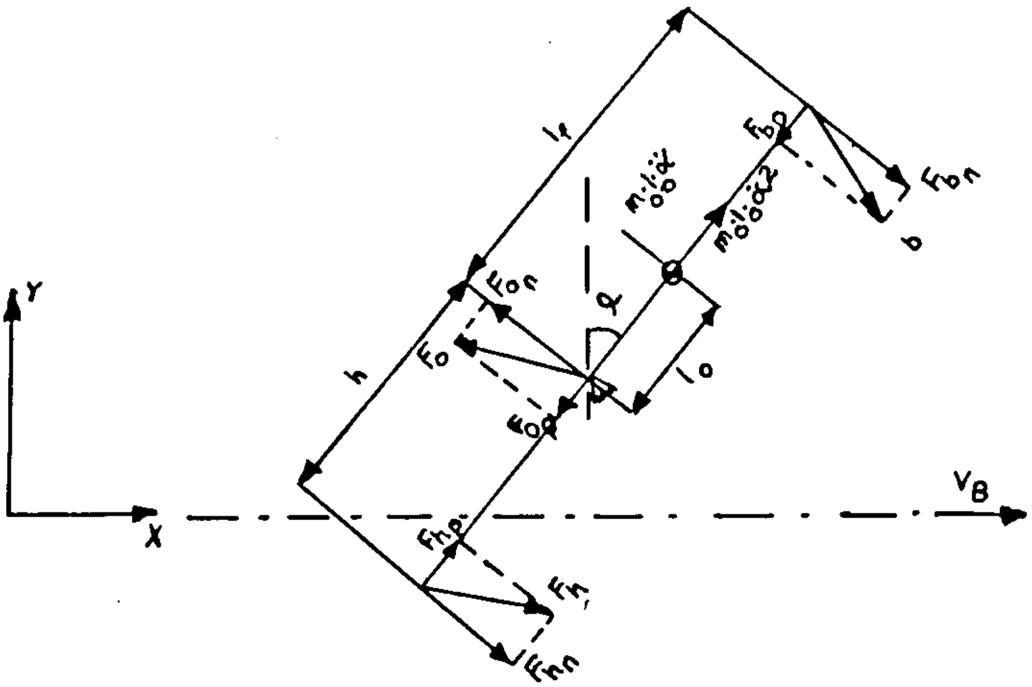


Figure 9 The forces acting on the oar (Dal Monte and Komor, 1988, p.72)

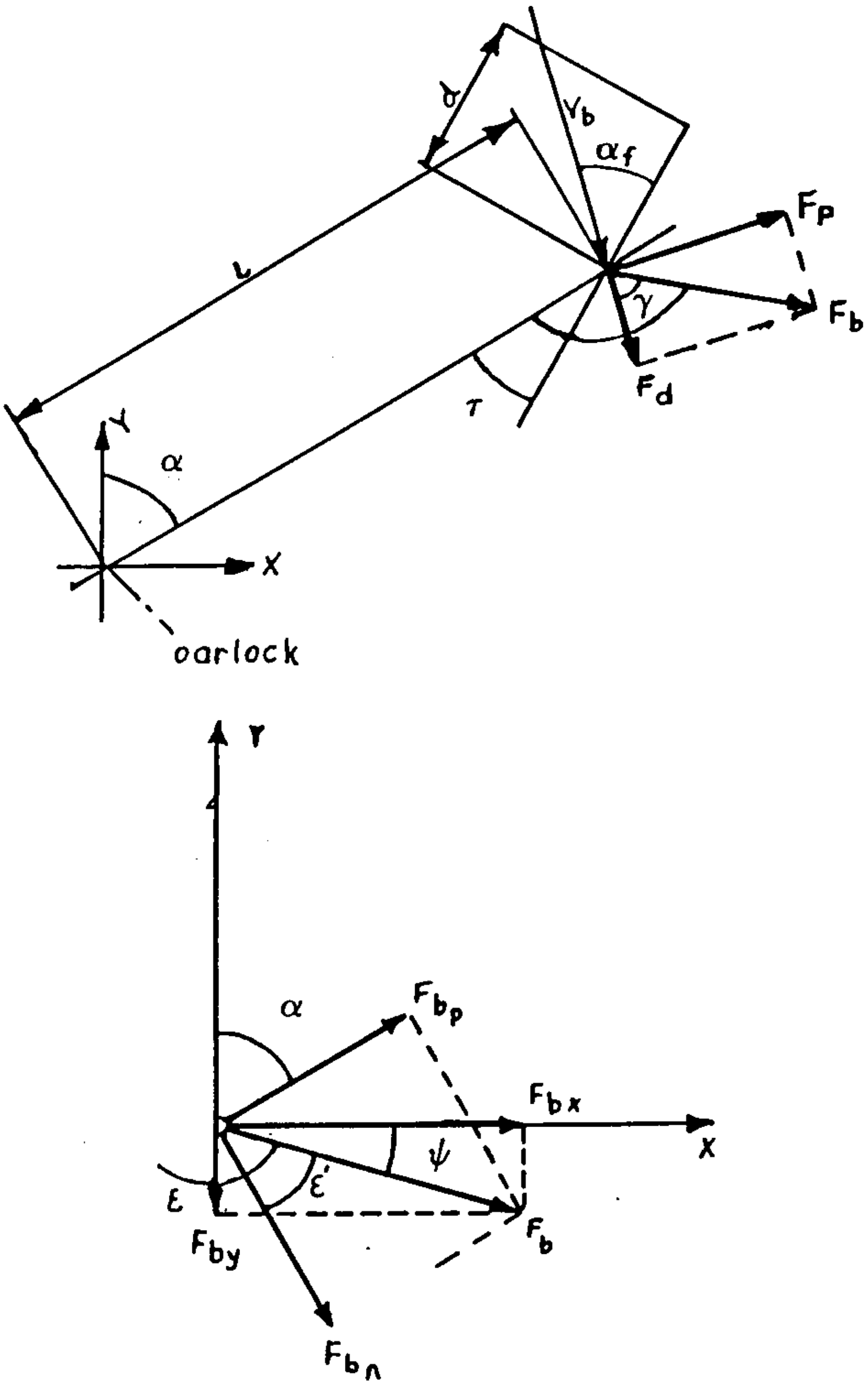


Figure 10 The forces acting on the blade of the oar (Dal Monte and Komor, 1988, p.73)

direction as the boat movement thus assisting progression. The second component acts at right angles to the first. This force acts to strain the boat and does not assist propulsion.

(2) The force exerted by the rower in the direction of motion of the boat.

(3) The resistance to progression considered as the force applied to the oarlock (or thole) pin which is rigidly attached to the boat via the rigger.

(4) The oarlock reaction to the perpendicular force as previously mentioned.

(Celentano, Cortili, Di Prampero and Ceretelli, 1974; Leighton, 1983)

The oar is the main propulsive unit of the boat-oar-rower system (Bompa, Hebbelink and Van Gheluwe, 1985) and the forces acting on the oar have received the most attention from researchers. Figure 11 indicates the typical shapes of external forces acting on the oar handle, the oarlock and the blade.

### Oar force measurement in rowing

A variety of measurement techniques have been utilized in the assessment of the external forces acting on the oar. For example, the measurement of oarlock forces has a history stretching back to the early 1900's involving a variety of instrumentation methods (Baird and Soroka, 1951; Edwards, 1963; Leighton, 1983; Dal Monte and Komor, 1988).

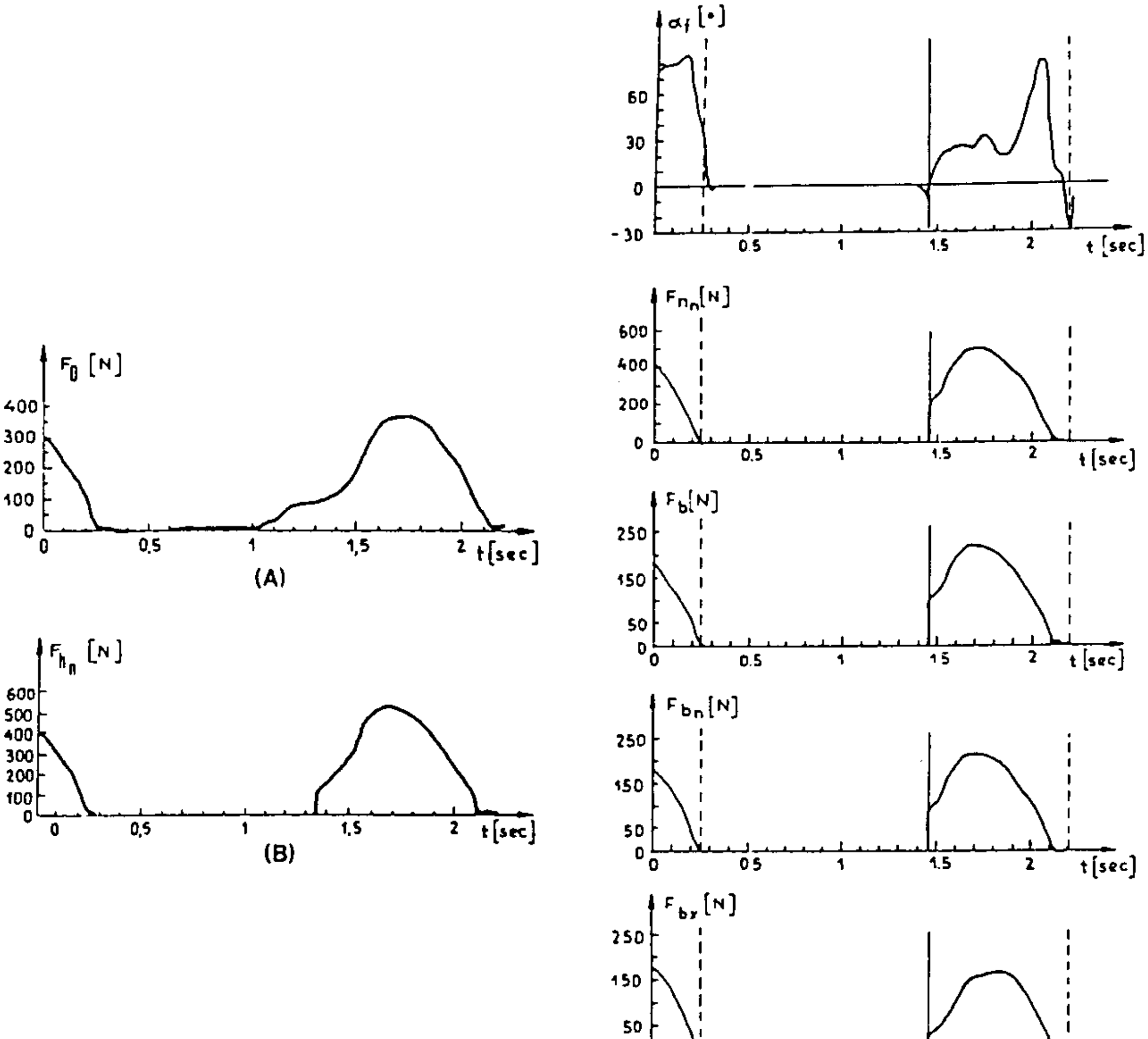


**Figure 11** Typical shapes of forces acting on the oarlock (A), the oar handle (B), and the blade (C) (Dal Monte and Komor, 1988, p.75-76)

One of the earliest reported studies of the forces generated by the rower at each part of the rowing stroke was undertaken by Cameron (1967). While the author recognized the value of strain gauges or load cells, a photographic analysis method was utilized. Oar deflection during the rowing stroke was recorded by high speed photography as the boat was rowed under a bridge with oar flexibility being calibrated by static loading. The resultant force analysis indicated that the force was nearly constant throughout the stroke. Subsequent research (Ishiko, 1971; Leighton, 1983; Smith et al. 1988) has not substantiated these findings. The use of photographic techniques to analyze the biomechanical aspects of rowing has been criticized (Schneider, Morell and Sidler, 1978) due to extensive equipment needs and the lack of precise results.

More accurate force testing of rowers was made possible with the use of strain gauge techniques. Baird and Soroka (1951) developed a modified oarlock pin containing strain gauges which were used to amplify the strain in the direction parallel to the motion of the boat. The modified oarlock pin was sensitive to torsion in the oar with forces applied on the oar handle and pressure changes over the surface of the blade resulting in force amplification. Noise induction was found to be a problem and the force-time plots were unusually variable (Leighton, 1983). A similar measurement system was utilized by Celentano et al. (1974). Strain gauges that were attached to the inboard fore and aft faces of the oar were also used by a number of researchers (Edwards, 1963; Ishiko, 1971; Schneider, 1980; Schneider et al. 1978) to measure the forces generated by the rower by recording the degree of oar deflection.

Ishiko (1971) measured the forces on the blade with a Wheatstone bridge connected to a DC amplifier and then used telemetry to convey the signals received, via an FM transmitter, to a shore-based recorder. The system was calibrated by hanging various weights at the grip and recording the current change on the strain gauges. This system allowed approximate determination of the muscular forces exerted on the oar. Unfortunately, the flexing of the oars and the shell meant that the forces to be measured could not be effectively isolated. Oar mounted strain gauges have also been found to be sensitive to twisting of the oar due to the non-symmetrical cross section and non-homogeneity of the oar (Leighton, 1983).

Celentano et al. (1974) assumed that the forces acting on the oar and boat could be determined by measuring the stresses on the oarlock pin. The authors used a direct rigger based measuring system, whereby the data generated on the boat was directly transmitted to a following power boat via a 20 metre insulated cable.

Schneider, Angst and Brandt (1978) recorded the force profiles of different oarsmen in pair-oar boats. Strain gauges and potentiometers were mounted on heavy duty rigging and data ~~was~~ were transmitted to the coach's boat or to the shore. Data was not decoded or analyzed until after the rowing effort and the system used was somewhat bulky and complex.

Schneider and Howald (1978) and Schneider and Hauser (1981) plotted the power output of the rower as a function of race duration. The researchers utilized a system whereby force data was collected on a FM tape recorder and then analyzed on a home computer. This system was referred to as the Environmental Data Acquisition System (EDAS) (Klavora, 1979b).

Schroder (1981a) utilized a system similar to Celentano et al. (1974), however, in later studies (1981b, 1983a) the link with a trailing power boat was dispensed with and data recordings were made directly on an outrigger attached to the boat with a tape recorder in the boat interfaced with a computer for data analysis. A further modification of this system (Schroder, 1983b) was developed for use in a sculling boat.

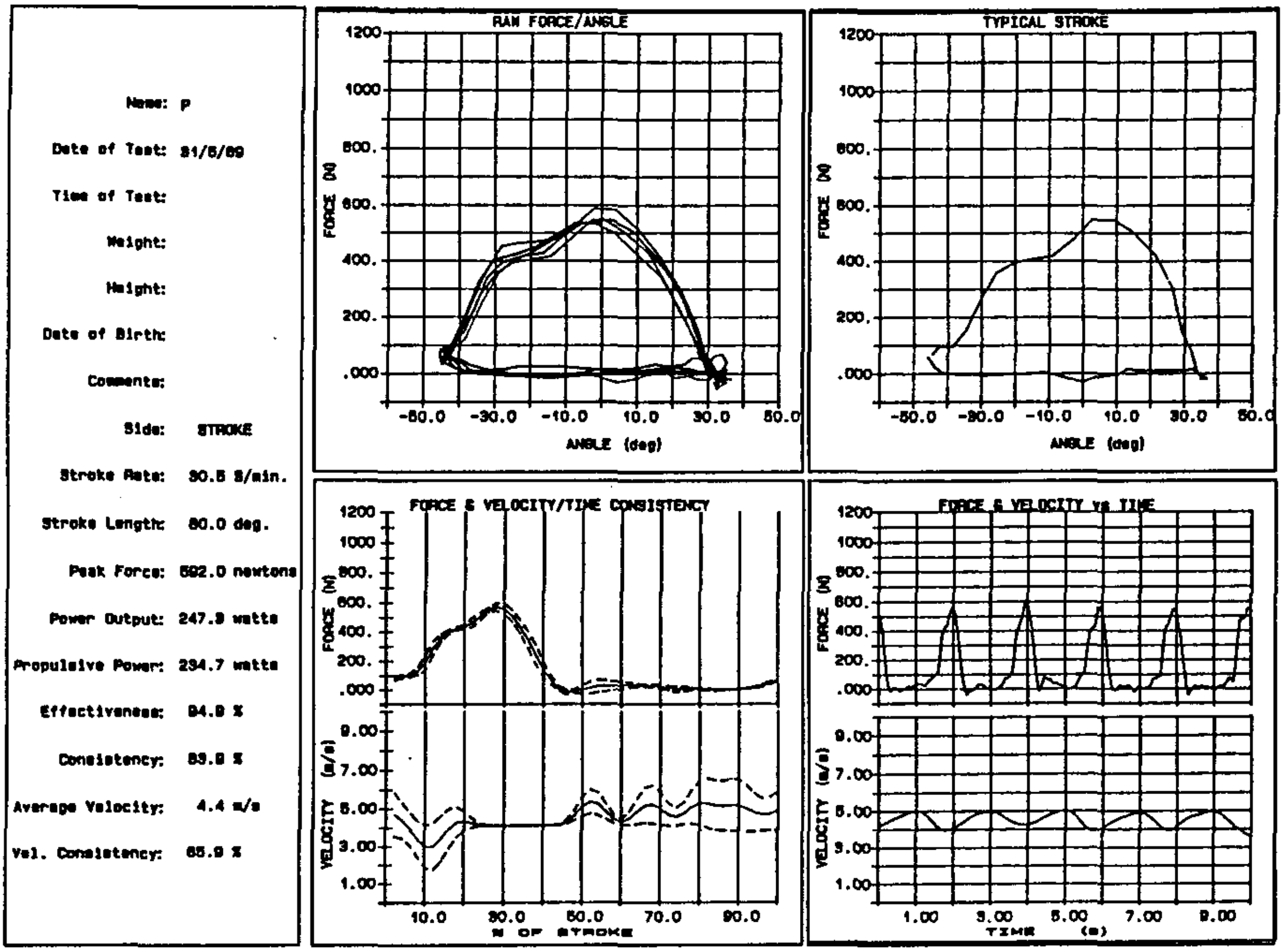
Leighton (1983) developed rigger based transducer modules which effectively isolated the force component parallel to the boat motion direction. These modules were not sensitive to torsion along the oar length, vertical forces or transverse forces. The oar angle at each position during the stroke was recorded accurately by a potentiometer driven by a gear on the oarlock. The author also utilized an FM (2 channel) recording system with a variable cut-off (6 Hz to 60 Hz) frequency filter allowing system noise to be filtered while retaining the essential signal content.

The above studies were based on the premise that force measurements made at the oarlock pin were indicative of force application in the water. All of these studies required specially instrumented oarlocks or oars, which, while providing accurate information, were not readily adaptable to normal rowing conditions. The rower was required to adapt to the equipment thus ignoring individual preference for oar and blade types, and there was also considerable delay in providing meaningful information for the coaching process.

Recent research (Gerber et al. 1985; Smith et al. 1988; Smith and Spinks, 1989a) has resulted in the development of a highly accurate, lightweight and portable system which can be quickly mounted on any oar, oarlock or boat. Oar force was determined by measuring the strain produced in the oar with a linear proximity transducer. Oar angle was determined via a rubber band electrogoniometer. Signals measured on the boat were amplified and then sent via telemetry to a shore-based computer for further processing. A water speed transducer was also used to determine boat velocity. This system allowed multi-oar evaluation with the rower using familiar equipment and provided immediate post action feedback of force, angle, force/angle, velocity and acceleration parameters (Gerber et al. 1985; Smith et al. 1988). A sample output from one of these instrumentation systems (Smith and Spinks, 1989a) is presented in Figure 12.

An on-water computerized biomechanical analysis system was used by Bachev, Tsvetkov and Boichev (1989) to determine maximal force applied on the oar handle, average force, the force maintained at 80% of the maximal force and the duration of the force maintained at 80% of the maximal force. The system was based on an oar-mounted tensiometer and oar angle sensor. Initially, the feedback provided was delayed but a modification of the system allowed for immediate feedback in the form of a light or sound indication of performance. This system allowed the coach and rower to measure and immediately control the force applied to the oar handle within a range of 100 to 1000 newtons. The indicators were used to provide feedback of efforts within a 30 or 60 newton increment range, a rotation angle of 40 degrees or the derived propulsive force.

Christov, Ivanov and Christov (1989) developed an on-water biomechanical analysis system (single scull) to compare on-water, rowing tank and rowing ergometer (Gjessing) measures for the force applied to the oar handle, angular displacement of the oar, boat acceleration and boat velocity. Force-angle curves, averaged over a cycle of 25 curves, were examined for the position of the maximal force and the volume of the catch and finish phases of the force-angle curve.



Name: p

Date of Test: 31/5/89

Time of Test:

Weight:

Height:

Date of Birth:

Comments:

Side: STROKE

Stroke Rate: 30.5 S/min.

Stroke Length: 80.0 deg.

Peak Force: 592.0 newtons

Power Output: 247.9 watts

Propulsive Power: 234.7 watts

Effectiveness: 94.9 %

Consistency: 83.9 %

Average Velocity: 4.4 m/s

Vel. Consistency: 65.9 %

Figure 12 Measurement system output for oar force, oar angle and boat velocity (Smith and Spinks, 1989a, p.284)

Duchesnes, Borres, Lewillie, Riethmuller and Olivari (1989) took advantage of progress in the miniaturization of electronic components to develop an on-water biomechanical analysis system based on that described by Baird and Soroka (1951). The system was designed to be cheaper and less complicated than the multichannel telemetry techniques used by Ishiko (1971) and Schneider et al. (1978). This system recorded the acceleration of the boat, the component of force useful for progression of the boat (represented as the force-time curve) and the angular displacement of the oar.

Komor and Leonardi (1988) utilized a computer-aided instrumented rowing ergometer (Giesing-Nilsen) to examine various parameters of rowing performance. An 8 channel A/C converter connected to an Apple IIe (or IBM PC) personal computer provided real time analysis of rowing kinematics, oar handle force, trajectory of the oar grip, seat movement, reaction forces on the stretcher and seat, load simulator characteristics and synchronization parameters. Off-line analysis allowed determination of stroke by stroke measures for stroke time, peak pull force, work, pull power and pull force impulse. Further analysis took into account a general rowing performance index, a stroke regularity factor, and a similarity index for crew selection purposes. The authors stated that the computer-aided system can play a significant role in technique improvement for both novice and elite rowers.

A system similar to the above has been developed by Smith and Spinks (1989b) for the Concept II rowing ergometer. Force on the oar was measured with a load cell attached in series with the ergometer chain while oar angle was measured with a rubber band electrogoniometer using a 10 kilohm servo potentiometer. Force and angle data were sampled continuously at 25 hertz via an analogue to digital converter and processed by an MS-DOS computer. Force and angle data were further processed to determine values for stroke rate, stroke length, peak force, work done, propulsive work, stroke-to-stroke consistency, stroke smoothness and propulsive work consistency in a manner similar to that developed previously for on-water analysis (Smith and Spinks, 1989a). The system was designed to provide the rower and the coach with concurrent visual feedback, via an oscilloscope, of the force on the oar handle and the position of the oar.

Recent years have seen increasing utilization of advanced electronics and computer systems in biomechanics research in rowing. Computer-technology advances have allowed the development of sophisticated computer-aided measurement systems for both on-water and on-shore assessment of rowing capacity and skill. Increasingly, the focus is on limiting factors in rowing and on objective evaluation of rowing technique. As the main propulsive unit, the focus remains on the forces applied to the oar by the rower.

### Force analysis in rowing

The qualitative assessment of rowing technique has traditionally centred on the extent to which the rowers adopted style varies from an accepted "rowing style". The rowing literature abounds with detailed descriptions of various rowing styles based on the observed relationships between the kinematics of the rower and the progress of the boat. These styles include the English Orthodox, Fairbairn, Adam, German Democratic Republic (GDR or Modern Orthodox), Rosenberg and Tsukuba styles (Dal Monte and Komor, 1988; Edwards, 1963; Fukunaga, 1984; Klavora, 1982b; Martin and Bernfield, 1980; Pannell, 1972; Schneider, 1980).

A more quantitative classification of rowing styles may be based on an analysis of the shape of the forces generated by the rower on the oar handle or the oarlock (Dal Monte and Komor, 1988; Leighton, 1983). The information provided by oar force analysis has been seen by a number of researchers (Angst, 1984; Angst et al. 1985; Gerber et al. 1985; Leighton, 1983) as being important for the evaluation of rowing technique and crew selection . As indicated by Leighton (1983), three main types of force information are available, namely:

(1) Force-time profile. This provides information concerning the rower's strength, stroke rate and the ratio of drive time to recovery time. Force magnitude and the time taken to reach maximum force following the catch may also be ascertained.

(2) Oar angle-time profile. This measure allows analysis of the

angular motion of the oar. Stroke length, angular speed of the oar, drive to recovery time ratio, stroke rate and stroke rate variability may be determined.

(3) Force-oar angle profile. Allows examination of the force applied by the rower at each stage of the stroke as well as the rate of work output for a specific effort. The force-angle profile is derived by plotting the force applied by the rower on the oar handle (force-time curve) as a function of the oar angle (angle-time curve).

Figure 13 indicates force curves consistent with the above parameters (Leighton, 1983). Force curves allow determination of peak force, impulse (area under the curve), stroke rate, slope of the force curve, and catch and finish synchronization. High forces applied for a sustained period of time are represented by a large area under the curve. Force curve analysis also allows determination of oar angle and boat speed parameters. The boat speed increases during the drive phase with maximum speed being reached as the blade is removed from the water (initiation of the recovery phase). During the recovery ("run") phase, the boat speed decreases with maximum deceleration occurring at the catch. The relationships between these variables are outlined by Angst (1985) (see Figure 14).

Ishiko (1971) examined the effects of increased stroke rate on the force-time curve and found that the curves were very similar between 38

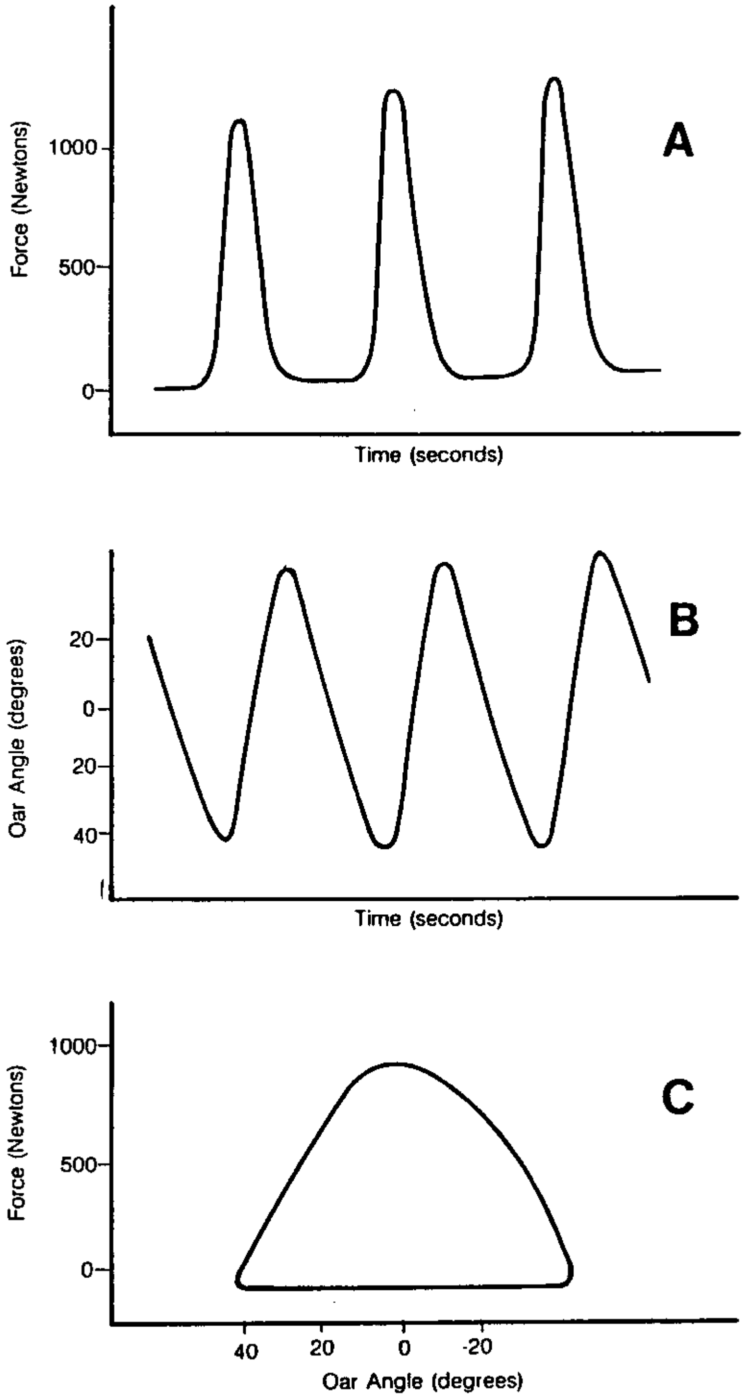


**Figure 13** Oar force analysis information in rowing; (a) force-time, (b) oar angle-time, (c) force-oar angle (adapted from Leighton, 1983, p.49)

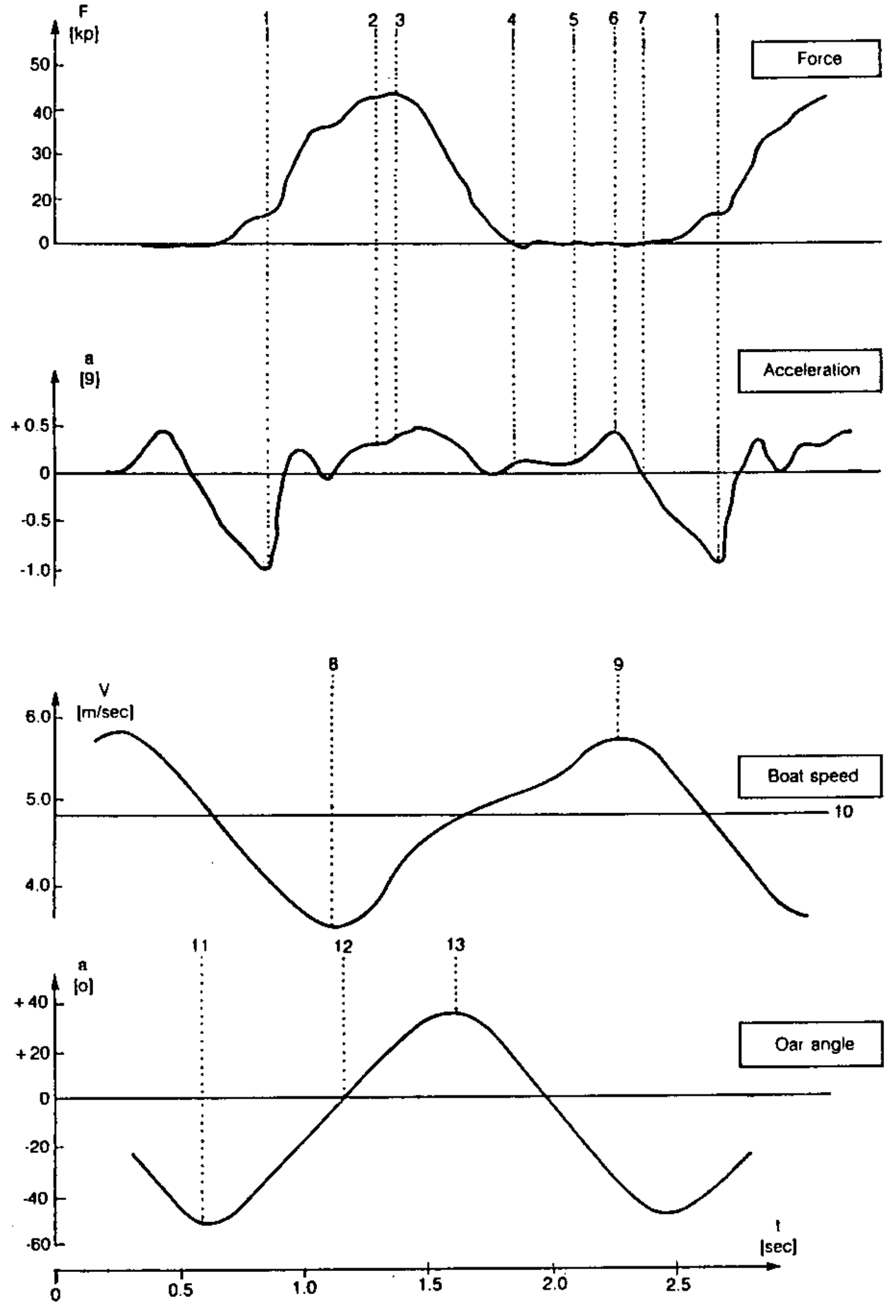


**Figure 14 The relationships between the force curve and boat speed, acceleration and rowing angle (adapted from Angst, 1985, pp.10-11)**

[1] & [11] = beginning of catch; [2] & [12] = oar vertical to longitudinal axis of boat during drive phase; [3] = peak force; [4] & [13] = end of drive phase; [5] = beginning of recovery phase; [6] = oar vertical to longitudinal axis of boat during recovery phase; [7] = maximum speed; [8] = lowest speed; [9] = average speed during one stroke; [10] = highest speed after recovery phase.

and 42 strokes per minute with increases in stroke rate leading to a greater reduction in the recovery phase time than in the drive phase time. It was determined that a higher stroke rate leads to the application of force over a longer period of time rather than a substantial increase in force magnitude.

The author also found that the force-time curves of all rowers showed considerable individuality, with significant variation in the time of peak force, force pattern application and force-time curve shape. It was suggested that a greater coincidence of drive phase force-time curves could lead to the improved performance of a crew.

Electromyographic analysis was utilized by Smith, Stevenson, Bergmark and Walsh (1987) to determine that the pattern of muscle activation during rowing is closely related to the shape of the force-time curve and that both are consistent from stroke to stroke and unique to each individual.

When Mason, Shakespear and Doherty (1988) compared effective force against oar displacement, they noticed "that each rower possesed a clearly distinctive curve and that matching of subjects could be done on the basis of the shape of this curve" (Mason et al. 1988, p.8).
In terms of force-angle requirements, Ishiko's (1971) work confirmed that peak force should occur when the oar is at right angles to the boat. From the coaching perspective, this characteristic was apparent

slightly after this position due to bend in the oar. Celentano et al. (1974) examined both the rotary and translatory components of the rowing stroke and stated that when the oar is not at 90 degrees to the keel, the effects of the applied forces are reduced as they are not acting in the desired direction of travel. The authors agreed with Ishiko (1971) in that elite rowers were found to maintain a relatively constant drive phase over a range of stroke rates. Increases in boat speed were attributed to increases in stroke rate with this increase being largely due to the oar being out of the water for a reduced period of time.

Schneider et al. (1978) saw the advantages of matching rowers with similar force-time curves in two man boats. A good correlation was found to exist between ergometer power recordings and race performance and Schneider (1979) went on to summarize those features of the force-time curve applicable to the coaching process:

(1) Force-time curves are highly individual in much the same fashion as handwriting style.
(2) Force-time curves with only one peak are preferable for boat propulsion.
(3) There is little variation in the overall shape of force-time curves during a race except towards the end of the race where fatigue affects style.
(4) Peak force allows measurement and comparison of work intensity amongst rowers with similar force-time curves.

Film and videotape records of rowing performance are commonly used by rowing coaches for technique correction. However, Angst (1980) found that coaches were unable to accurately determine, from a film source, the technical elements of the catch involving the immediacy of the reversal of the blade and the first contact with the water. The author described an alternate analytical procedure whereby film of the rower's action was used to create a series of stick figures (or cinegram) by drawing straight lines between the elbow, shoulder, hip, knee and ankle joints and the inboard end of the oar. The first stick figure was drawn at the moment of the catch and subsequent figures at each quarter of the drive and recovery phases. By tracking the inboard end of the oar throughout the stroke, a hand curve was also produced. Thus it was possible to compare rowing technique with the passage of the oar and the force generated on the oar handle. By comparing the hand curve with an efficient force-time curve, an "ideal" hand curve was produced (see Figure 15).

Angst (1984) was able to demonstrate that the essential features of force-time curve produced in a rowing tank are the same as those produced in the boat. These force-time curves were utilized by the author to determine and eradicate faults in rowing technique. However, Leighton (1983) saw force-angle profile analysis as providing greater insight into the human-machine relationship in rowing. The characteristic features of the force-angle profile were defined as follows:

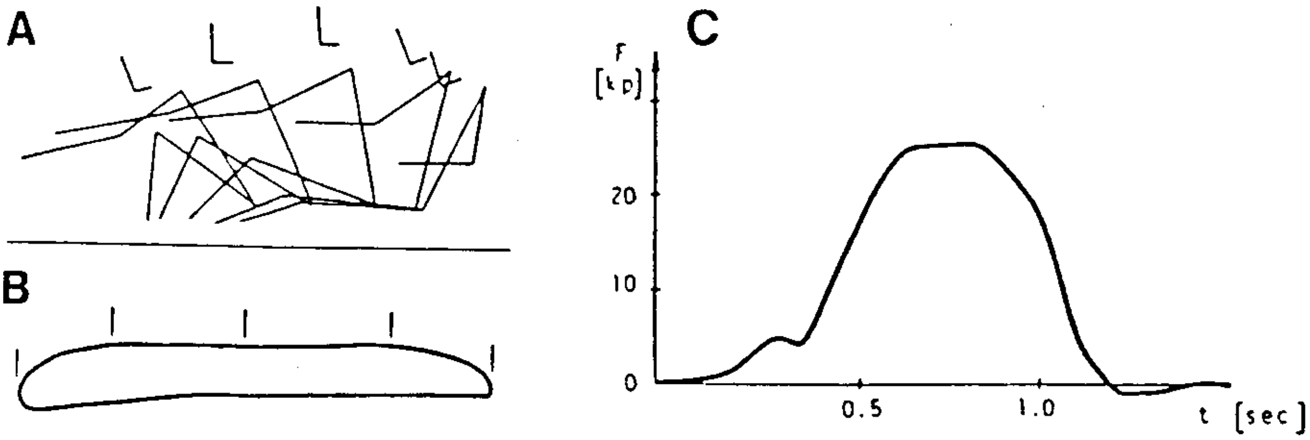


Figure 15 Cinegram (A), hand curve (B) and force-time (C) curve analysis of rowing technique (Angst, 1984, p.22)

(1) Stroke length. Stoke length was defined as the angle that the oar travels through as represented by the X-axis on the profile plot. The angle of the oar at the catch and finish was seen as being important for matching rowers as similar angle ranges lead to a smooth efficient drive.

(2) Peak force. Peak force was defined as the maximum recorded force as determined from the Y-axis on the profile plot. It was pointed out that the peak force does not indicate the work rate of the rower.

(3) Peak force position. Peak force position was defined as the percentage of stroke length that occurs before the peak force is achieved. Matching of rowers on this variable was seen as reducing the nett transverse thrust experienced by the boat close to the "square-off" position.

(4) Force continuity. The force continuity was defined as the percentage of the stroke length where the force exceeds 75% of the peak force. This variable was seen as being important for drive continuity and work output during each stroke.

(5) Catch force. The catch force was defined as the percentage of the stroke length prior to the force equalling 20% of the peak force. The speed of the force increase at the start of a stroke was believed to significantly influence rowing performance, for example, a very quick increase in force was seen as having the potential to upset boat balance whilst a slow catch might act to

decrease boat velocity resulting in increased skin friction drag as the wetted surface area of the hull increased.

(6) Finish force. The finish force was defined as the percentage of the stroke remaining after force reduction to 50% of the maximum force. This force was seen as influencing boat stability at the finish of the drive phase. Thus matching of rowers on this variable was believed to assist in negating nett transverse force.

The work output of the rower, important in determining eventual boat speed, was calculated as the total area under the force curve. Propulsive efficiency was determined by considering the oar angle and force at each part of the stroke. The force-angle profile continuity was seen as being indicative of boat stability along with the force applied at the start and finish of the stroke.

By developing a full appreciation of the importance of the above characteristics, Leighton (1983) believed that average boat velocity could be optimized. The force-angle profile was seen as being important for demonstrating to individual rowers those aspects of technique requiring adjustment in order to obtain maximum performance. The author also found that the force-angle profile shape varied considerably between rowers given individual differences in stroke characteristics including stroke length, peak force, peak force position, force continuity, catch force, and finish force. The range of parameters revealed by the force-angle profile are illustrated in Figure 16.

As previously determined by Leighton (1983), Christov et al. (1989) found that the three different work situations provided by on-water, rowing tank and rowing ergometer efforts produced varying force-angle curve shapes. Particular variance was noted for the position of the maximum force. However, no quantitative information was presented.

Further research (Christov et al. 1988) indicated that the shape of the force-angle curves and the magnitude of the biomechanical parameters (grip speed, pull force, slide speed, flywheel revolutions, foot reaction on the stretcher, body weight on the slide and neck speed) measured on the rowing ergometer were similar to those measured in the boat. The maximum force measured on the ergometer was 10%-15% greater than in the boat and occurred at the beginning of the drive phase. The occurrence of the maximum force at the beginning of the stroke was common to all elite rowers tested and this was attributed to a learning effect resulting from the regular use of the rowing ergometer during training. Force applied to the oar handle of the ergometer was 20%-25% greater than in the boat resulting in a change in the shape of the linear grip-velocity curve from more rounded to slightly "egg-shaped". The relationship between the drive and recovery phases of the rowing stroke was found to be 1:1.2 on the ergometer and 1:1 on the boat. This variation in the drive to "come-forward" ratio was believed to be

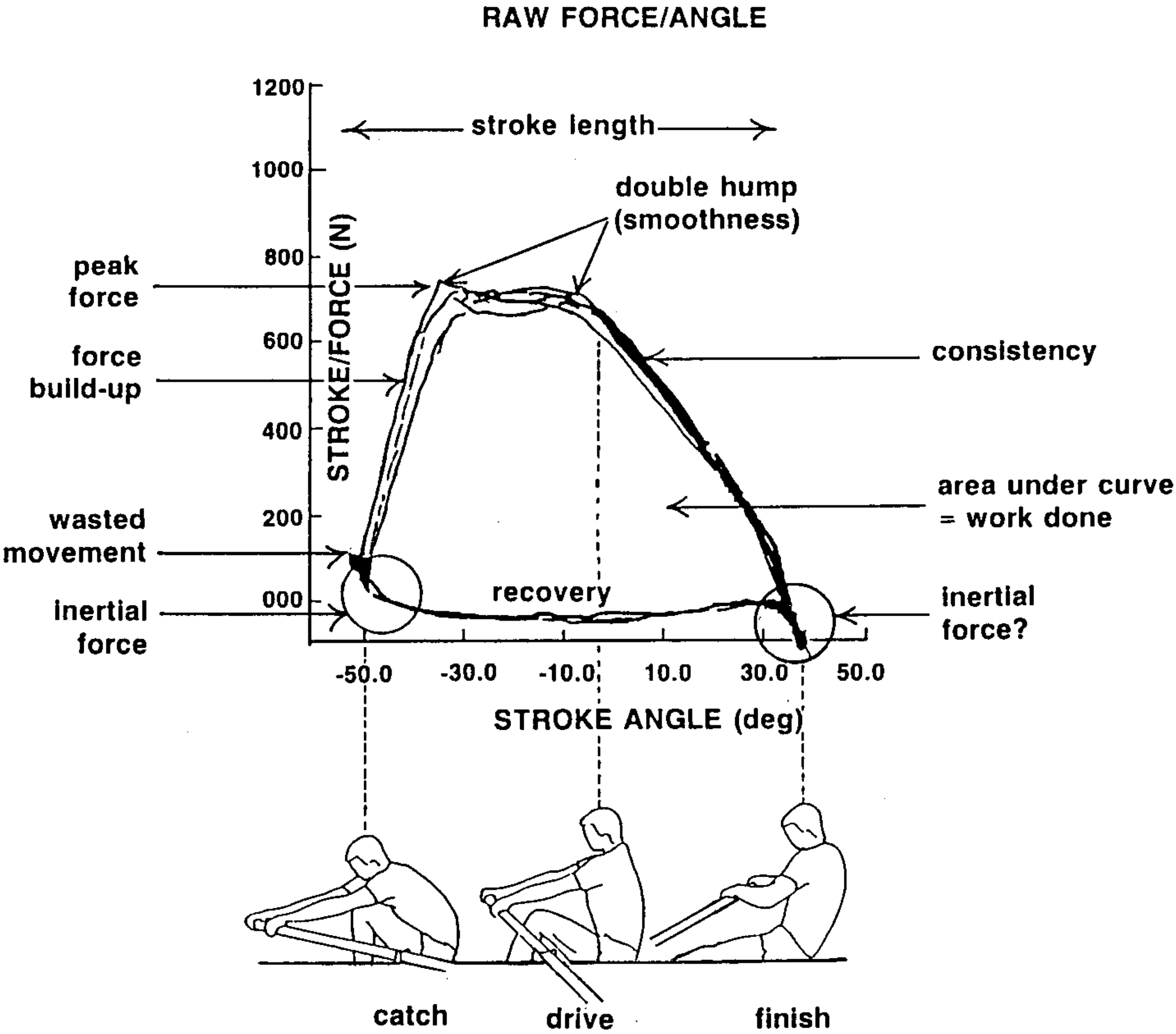


**Figure 16** The range of features revealed by the force-angle profile in rowing (Smith and Spinks, 1989, p.283)

due to the necessity to overcome the inertia of the mass of the body during the recovery phase for which time and force is necessary. The demands of this task were confirmed by subjective complaints regarding local muscular fatigue in the lower extremities.

Millward (1987) constructed a computer program to calculate the motion of the boat and to examine the effects of changes in force production on boat performance. It was suggested that previous information on the magnitude of the rowing force (Celentano et al. 1974; Schneider et al. 1978) was inadequate for the construction of a model of the cyclic variation of the rowing force. Information concerning the variation in rowing force throughout the stroke, the relationship between drive time and recovery time and the inter-individual variability in the shape of the force-time curve was considered to be necessary for an effective model of the rowing force. Millward's computer model was in close agreement with the available data, even though the effect of the sliding mass of the rower in the boat namely, the damping of speed oscillation through the stroke cycle, was not considered. Application of the derived model indicated that if a quarter of the power wasted during a rowing stroke was actually used for propulsion then an increase in speed to 4.6 metres per second could be expected for the same peak rowing force (308 newtons) resulting in a lead of 5 seconds at the finish line. The adoption of different shaped force-time curves showed that the shape of the curve was of greater importance than the peak force value. It was determined that a flatter, wider curve required a much lower peak force value to produce the same boat speed as two other curves with steeper gradients. Close examination of the shape of individual force-time curves was suggested by the author. A series of calculations were undertaken to examine the relationship between drive and recovery time where the maximum force and the shape of the force-time curve were kept constant but the time between drive and recovery was varied. It was suggested that the time spent in the recovery phase should be reduced in line with the physical attributes of the rower. More detailed study of these areas was recommended in order to determine if the suggested changes are within the physical capability of the rower. The present study addresses in part, the author's concerns about power wastage and examination of individual force curves.

A factor analysis of the main variables limiting the performance of a single scull rower was used by Bachev et al. (1989) as the theoretical base for a computerized on-water biomechanical analysis system. In all, five factors were identified, the first being a "force factor" which represented the sum of the mean forces applied by the left and right hands and which explained 38.9% of the dispersion. The second factor was called the "velocity factor" which indicated the proportion between the mean and inner-cycle velocity of the boat and accounted for 17.5% of the dispersion. The third factor was a "time-force" factor which indicated the time taken for the application of force during the drive phase of the stroke and which explained 14.7% of the dispersion.

The fourth factor was termed the efficiency of the "pull out of the oar" and referred to the decrease of the applied force below 80% of the maximum force up to the release of the oar. This factor explained 8.9% of the dispersion. The fifth factor was concerned with the "efficiency of the stroke" which accounted for 7.3% of the dispersion and which is limited by the negative acceleration of the boat. All factors together accounted for 87.3% of the total dispersion.

As pointed out by Bachev et al. (1989) the relative contribution of these factors are subject to variation as rowers improve their rowing technique. Therefore, it was considered necessary to undertake periodic biomechanical assessment of the rower's performance.

Mason, Shakespear and Doherty (1988) examined the impact of training on effective work rate, effective work output per stroke and stroke rate for elite female rowers (N=8). This study also examined the relationship between effective force and effective work output and between effective force and effective power. Effective work output was defined as that portion of the total work used to move the boat in a forward direction. The rowers were tested prior to the commencement of the training season and again following one month of intensive training. The training program was designed to enhance aerobic capacity and rowing technique. Oar force and displacement data were collected during a 7 minute maximal rowing ergometer test. Previously collected kinematic data gathered via overhead cinematography, allowed computation of effective force profiles from the kinetic information derived from the ergometer test. This allowed the determination of effective work and effective power.

Over the period of this study, there was a significant ($p<.02$) increase in total effective work output and the effective work output per stroke. There was no increase in stroke rate, in fact there was a tendency to decrease the stroke rate. The rowers who developed a more even effective force profile showed a tendency to possess a higher effective work output. It was determined that it was possible to match rowers according to their work output and effective force profiles. The effective power profile was found to be no more informative than the effective force profile.

Data collected by Duchesnes et al. (1989) was limited to an average of eight consecutive strokes for one female rower rowing lightly at 20 strokes per minute. However, preliminary results were in agreement with those of Ishiko (1971) and confirmed what was known about the length of the drive phase and the relationship between the movement of the rower on the slide and the acceleration of the boat. The appearance of a second force peak was tentatively seen as being due to inadequate coupling of muscular activity between the legs and the trunk.

It appears that knowledge of individual force-angle profile characteristics would be of significant value to the coach in providing information that is not readily available, that is, an understanding of what is happening during the interaction of the oar with the water. For example, even though coaches can see the mound of water created by the blade pressure, they are unable to quantify what is happening and thus must attempt to link the kinematics of the rower's movements with the observed pressure of the blade on the water. It is possible that the style displayed by the rower may not truly reflect the effectiveness of the stroke, with the coach making technique corrections based on inadequate and/or misleading information.

Additional information available from force-angle data includes the accuracy with which the rower traces the force-angle profile stroke by stroke (stroke-to-stroke consistency), the smoothness with which the force is applied during the drive phase of the stroke, and the flatness (or "evenness") of the power output curve (propulsive work consistency). Propulsive work consistency relates to the pattern of energy expenditure. From a physiological viewpoint (Ariyoshi, Yamaji and Shephard, 1979; Klavora, 1979a) the most effective method of energy expenditure is to obtain a power output level slightly above the mean level at the beginning of the effort, and to maintain a slightly decreasing power output throughout the effort.

The literature (Angst, 1984; Williams, 1967) suggest~~s~~ed a connection between the smoothness of the force-angle profile and the smooth transfer of applied force between leg, trunk and arm segments. Smooth force-angle profiles may also be connected with (a) larger areas under the curve and thus higher work output; (b) reduction of transverse oscillatory forces on the boat; (c) reduction of hydrodynamic drag resulting from disturbances affecting the straight line trajectory of the boat; and (d) reduced deviations from the mean velocity of the boat.

Having identified certain biomechanical variables that contribute to performance in rowing it remains to determine the relative importance of these variables and the extent to which knowledge of these variables can be used to enhance performance.

In the laboratory determination of maximal work capacity for rowing it is important to select equipment which closely replicates the inherent rowing action. It is also important to design test procedures which closely correspond to actual competition in terms of action, intensity and duration (Tumilty, Hahn and Telford, 1987). Therefore, the most reliable procedure would be to determine work capacity measures during a maximal rowing performance to ensure optimal utilization of the specifically trained muscle fibres (Stromme, Ingjer and Meen, 1977).

## Work capacity analysis in rowing

A number of methods have been used to measure the work capacity of rowers. These have included actual on-water rowing, rowing in a training tank, treadmill and bicycle ergometer tasks and simulated rowing on a mechanical rowing ergometer.

Early on-water studies (Hagerman and Lee, 1971; Di Prampero et al. 1971; Stromme et al. 1977) were concerned with the physiology of rowing and utilized the relationship between heart rate and oxygen uptake via telemetric recording of heart rate. While direct measurement of oxygen uptake via the Douglas bag technique was attempted in single scull, double scull and pair oared boats (Jackson and Secher, 1976; Stromme et al. 1977) logistical problems made such a procedure impossible in four and eight oared boats (Hagerman et al. 1978).

Rowing tank information was gathered by Hagerman and Lee (1971) and Di Prampero et al. (1971). However, Di Prampero et al. (1971) concluded that rowing in a tank with practically still water was an entirely different process than actual rowing, from both a mechanical and physiological viewpoint. The authors found that the stroke rate was higher in the tank than in actual rowing and this led to a high level of wasted energy due to an increase in transverse force and the greater energy needed to move the rower's body as the stroke rate increased. It was suggested (Di Prampero et al. 1971) that for tank rowing to simulate actual rowing it was necessary to take the geometry and shape of the blade and the hydrodynamics of the tank into account. It was also suggested that the water in the tank be moved at known speeds. This was done by Asami et al. (1978) who utilized a water circulation speed of 4 metres per second. Jackson and Secher (1976) stated that reduced working capacity while rowing in stationary water may be attributed to excessive water resistance and resultant local muscular fatigue which prevents large workloads from being obtained.

Hagerman and Lee (1971) found that a larger body mass seemed to favour increased work output in the rowing tank as smaller subjects found it difficult to maintain the set stroke rate of 33 strokes per minute at the required catch pressure. It appears that in tank rowing, increased mass does not contribute to increased resistance as is the case in actual rowing. The authors found it difficult to achieve comparative conditions between the on-water and the rowing tank situations. They believed that the difficulty arose from a slower positive water flow rate than normally experienced on-the-water and over-reaction of the subjects to the tank situation, which was reflected in significantly higher heart rate measures.

Stromme et al. (1977) compared on-water performance with treadmill measures and found that most oarsmen attained higher maximal oxygen uptake measures during actual rowing with the mean difference being 0.23 litres per minute (4.2%) and the largest difference observed being 0.89 litres per minute (14.3%). Secher et al. (1982), considered that maximal oxygen uptake values for well trained oarsmen, determined during running or bicycling, would be 200 millilitres smaller than would be expected during rowing. However, comparisons between treadmill, bicycle ergometer and rowing ergometer results have produced conflicting findings. Carey, Stensland and Hartley (1974) found that the same maximal oxygen uptake could be generated during rowing (5.32 litres per minute) and treadmill running (5.34 litres per minute). On the other hand, Cunningham et al. (1975) reported slightly higher values when using the bicycle ergometer as against the rowing ergometer with the average difference in maximum oxygen uptake being 0.27 litres per minute. This is an interesting result as maximal oxygen uptake measured on bicycle ergometers is usually somewhat lower than values obtained by treadmill tests (Astrand and Rodahl, 1977).

Carey et al. (1974) were of the opinion that the rowing ergometer may not be the best method of determining maximal work capacity as there may be less muscle mass involved (particularly the legs) than in running. Also the stroke rate of 32-36 strokes per minute was seen as representing intermittent work in comparison to running. Cunningham et al. (1975) also stated that the rowing ergometer may not be able to simulate all aspects of the rowing activity as in a boat, the argument being that the mechanics of effectively transferring power to the blade while the boat moves through the water cannot be duplicated exactly. Rowing was described as a technically difficult exercise where slight discrepancies in mechanics might be crucial for the complete involvement of specifically trained muscle fibres and thus for the elicitation of maximal aerobic power (Stromme et al. 1977).

Although treadmill and bicycle ergometer exercises were seen by Hagerman, McKirnan and Pompei (1975) as providing valid and reliable maximal work conditions, the authors believed that these measures tend to underestimate aerobic capacity in some athletes. This was seen as being particularly applicable to technique based endurance sports such as rowing where the emphasis is on repetitive muscular efforts of the upper extremity. Rowing ergometer tests were seen by Hagerman et al. (1975) as simulating actual rowing conditions with a more accurate evaluation of maximal oxygen uptake.

Stromme et al. (1977) also considered that treadmill protocols were inadequate, particularly when the involvement of peripheral factors in the achievement of a high maximal oxygen uptake are considered, and especially when one is assessing athletes whose endurance fitness is based on the muscle groups of the upper extremities such as rowers.

This position was supported by Pyke (1979) who stated that bicycle work or treadmill running are not appropriate methods of assessment for rowers as improvements in performance capabilities of the muscle groups could go undetected on ergometers which fail to fully stress the specific muscle groups involved in rowing. Tumilty et al. (1987) compared the results of a 7 minute maximal test on a rowing ergometer with a progressive test on a bicycle ergometer and found that the peak oxygen uptake derived from the rowing ergometer was higher than that determined on the bicycle ergometer, the mean difference being 0.26 litres per minute (7.5%).

Christov et al. (1988) compared on-water and rowing ergometer performance and concluded that the rowing ergometer was a valuable instrument for the assessment and coaching of rowing technique, particularly for individual analysis of the work capacity and style of rowers in multi-seated boats. It was also determined that, as in the boat, individual rowers develop personal styles on the rowing ergometer.

Several authors (Christov et al. 1988; Hagerman et al. 1975; 1978; Hagerman, Hagerman and Mickelson, 1979; Pyke, 1979; McKenzie and Rhodes, 1982) have claimed that the rowing ergometer has been shown to accurately reflect the rowing task. Because of their ability to provide off-water simulation of the rowing action in a controlled environment, rowing ergometers have become an essential tool for the work capacity assessment of rowers. While enabling a close reproduction of the rowing action, the rowing ergometer does not facilitate exact reproduction and "feel" of on-water rowing. One of the main reasons for this situation is that the rowing ergometer remains stationary throughout the rowing stroke. In the on-water situation, the boat is free to move and its velocity is significantly influenced by the movement of the rower on the slide during each stroke. As described earlier, this effect is most apparent during the recovery phase of the rowing stroke when the boat experiences an increase in velocity following removal of the oar from the water and coincident with the rower's movement up the slide.

A solution to the lack of mobility is to mount the rowing ergometer on wheels that are aligned to its logitudinal axis. The provision of wheels leaves the ergometer free to move in a forward or backward direction in response to the movement of the rower on the slide thus allowing closer simulation of the "feel" of on-water rowing. Martindale and Robertson (1984) investigated this solution by conducting a cinematographical analysis of rowing performance on both a stationary and a wheeled Gjessing rowing ergometer. The authors found that the lack of motion in a stationary rowing ergometer caused rowers to accelerate and decelerate most of the body at each end of the stroke as well as moving the oar handle through the stroke. This is unlike actual rowing where the boat moves relative to the rower and where the rower's movements cause the boat to change its velocity relative to both the rower and the external reference system. However, the stationary rowing ergometer does not move in response to the rower's actions causing the rower's motion to be relative only to the external system of reference. The rower must come to a complete stop at the end of the slide and then must accelerate the whole body in the opposite direction for the recovery phase of the stroke.

By analyzing mechanical energy patterns and comparing them to the patterns generated when rowing single scull boats, Martindale and Robertson found that the wheeled ergometer allowed greater energy savings due to the ability to exchange energy between the body and the rowing ergometer. Similar (but greater) energy savings were found in the sculling trials indicating that wheeled ergometer testing more closely simulates actual on-water conditions than does a stationary ergometer.

The Gjessing rowing ergometer utilized in the above study is a "centre-pull" machine originally designed for scullers who manipulate an oar with each hand. Therefore, sweep oar rowers who utilize only one oar and whose style incorporates angling of the upper body inwards towards the rigger and slight twisting of the torso (Klavora, 1982a) must adapt to the varied demands of the Gjessing ergometer. On the other hand, the Repco rowing ergometer is more suited to sweep oar rowers as it has the traditional oar, oarlock and rigger arrangement.

Smith, Camden and Stuckey (1987) conducted a mechanical energy analysis of a wheeled and a stationary Repco rowing ergometer in order to determine if there were similar mechanical energy exchange advantages to the Gjessing ergometer (Martindale and Robertson, 1984). The authors demonstrated that greater energy exchanges occur when rowing a wheeled Repco rowing ergometer than when rowing a stationary one. The ability to exchange energy between the subject and the ergometer was seen as the source of increased energy exchange. The conclusion reached was that a wheeled ergometer may allow more effective utilization of total energy in doing work on the oar. It was recommended that future training and testing of rowers be conducted on wheeled rowing ergometers.

Different types of rowing ergometers, all of which may be equipped with the fixtures of a racing boat, may also consist of different forms of resistance, clutch and cam arrangements. These mechanical differences raise the question as to whether rowers are able to perform similarly on each type of ergometer. This is an important issue as any significant dissimilarity in physiological response to a standard rowing test would leave coaches and researchers in doubt as to which ergometer best simulated the rowing action (Hahn, Tumilty, Shakespear, Rowe and Telford, 1988).

Stuart (1984) compared the total work output recorded on a Repco and a Gjessing rowing ergometer for senior ($\underline{n}$=13) and lightweight ($\underline{n}$=8) male rowers and senior ($\underline{n}$=5) female rowers. Higher work outputs were recorded on the Repco ergometer. In terms of average power output (watts) the differences between the Repco and the Gjessing ergometer were 21.5% for the senior male rowers, 16.5% for the lightweight male rowers and 16.8% for the senior female rowers. Stuart stated that discrepancies in measured work output between two different types of rowing ergometers can be partly explained by the manner in which the two ergometers create their rowing resistance. The Gjessing rowing ergometer employs a resistance which is a relatively lineal concept related to the speed of rowing and the brake load on the flywheel. The Repco ergometer utilizes a vaned flywheel to generate load, this load being proportional to the velocity of the flywheel. The resultant curve is not lineal, (sic) but exponential as air resistance is proportional to the square of the velocity of the flywheel (Stuart, 1984). The author recommended that scores from different types of ergometers be considered independently when evaluating the work capacity of rowers.

Hahn et al. (1988) stated that the complex system involved in the transmission of energy from the "oar" to the flywheel in the Gjessing ergometer may lead to greater absorption of energy. It was also stated that there might be quite considerable variation between different Gjessing ergometers. The authors also suggested that performance on the Gjessing ergometer might be limited by local muscular fatigue thus resulting in insufficient demand on the central cardiovascular system.

Perhaps the most important feature of the rowing ergometer for testing purposes is the fact that it is used extensively as a training device with most rowers being familiar with its operation thus providing the "ideal stationary apparatus suitable for laboratory experimentation" (Hagerman et al. 1978, p.87). The current author's experience and that of Stuart (1984) and Hahn et al. (1988) is that rowers make their own subjective comparisons between ergometers, rating a machine on "degree of closeness" to the "real thing". For example, elite female rowers found the catch on the Gjessing ergometer to be "too hard" (Hahn et al. 1988).

Two important variables in the determination of work capacity for rowing are the types of work loads and work rates chosen to elicit the necessary response. The determination of work capacity is not only affected by the magnitude of the load (flywheel resistance, slope of treadmill, time on task, peak revolutions) but also by the work rate (pedal frequency, stroke rate, treadmill speed). In the surveyed research, there is a great deal of variability in the types of work tests chosen (Spinks, 1988).

Work output on rowing ergometers can be altered by changing the weight resistance, by altering the stroke rate and by exerting greater or less force on the oar. Hagerman et al. (1975) decided to use a constant resistance and increased the work load by increasing the stroke rate and by encouraging the rower to exert greater effort during the pull in order to more closely simulate the demands of actual rowing. Carey et al. (1974) chose a rowing ergometer test in order to ensure a steady rate of oxygen uptake and a maximum level of intensity. The load was chosen by "trial and error" from the coach's "experience" with the subjects. Neither the stroke rate nor the resistance for this test were mentioned, however, the authors described the 5 minute effort as leading to exhaustion. Cunningham et al. (1975) required their subjects to maintain a rate of 30 strokes per minute with the flywheel resistance modified to produce moderate (1.34 kilograms), heavy (1.82 kilograms) and maximal (2.27 kilograms) work.

Williams (1977) utilized a 6 minute maximal rowing ergometer effort at a rate of 30-33 strokes per minute with the accumulated stroke rate gathered for each minute. A flywheel resistance of 5.4 kilograms was used "since it closely resembled the load experienced in a top-level eight-oared race" (Williams, 1978, p.13). Hagerman et al. (1978) used a 3 kilogram flywheel resistance and instructed the subjects to row at a "competitive performance" level of 32-36 strokes per minute with a greater impetus on the oar which was specified as increased flywheel revolutions. Pyke et al. (1979) also used an "exhausting" 6 minute effort aimed at simulating a 2,000 metre rowing effort. However, no mention was made of stroke rate or peak flywheel revolutions.

McKenzie and Rhodes (1982) also simulated a 2,000 metre international class race in an eight-oared shell by imposing a 5 minute 45 second time limit on the maximal task. The effort was designed to simulate the race experience in time, pace and intensity of effort. A coxswain was present to ensure that the stroke rate, time and effort was maintained. Mickelson and Hagerman (1982) utilized a step-wise progressive test to exhaustion using the rowing ergometer (the first such test protocol reported). For a period of 15-18 minutes the stroke rate was limited to 28-32 strokes per minute with the flywheel spinning at a (near) constant 550 revolutions per minute (in order to keep the minute power increments at 27.0±5.0% watts). Each subject began at an initial power output of 47.2 watts (unloaded ergometer). After the first minute the power requirement was increased to 101.2 watts with the resistance being increased by 27.0 watts for each minute thereafter until maximal oxygen uptake was reached or the subject could no longer maintain the required revolutions per minute within the limited stroke rate range. The subjects had continual visual feedback of flywheel speed, total flywheel revolutions and elapsed time.

Mahler, Andrea and Andresen (1984) compared peak exercise physiological values determined for elite male rowers (N=12) during a 6 minute "all-out" effort and an incremental rowing ergometer test. Peak physiological values were determined during the first 2 minutes of the "all-out" test and in the last 2 minutes of the incremental test. There were no significant differences in peak values for heart rate, minute ventilation, oxygen uptake, carbon dioxide production and ratings of perceived exertion between the two test modes.

Williams (1977) stated that an important challenge in the exercise and sports science fields involves the recognition of the more important predictor variables that are related to a performance criterion and which increase the discriminating ability while keeping the number of variables to a minimum. For the purposes of this study, it was deemed necessary to determine the extent to which multivariate analysis of work capacity data has been used to recognize those variables influencing and limiting rowing performance.

## Multivariate analysis in rowing

Research in physical education and the exercise and sports sciences makes extensive use of the measurement and analysis of multiple dependent measures. Schutz, Smoll and Gessaroli (1983) surveyed 188 empirically-based journal articles in the above fields and found that approximately 70% of the articles cited the use of more than one dependent measure whilst more than 50% used five or more dependent variables. Despite the extensive use of multiple dependent measures only 40% of the studies used appropriate multivariate statistics, leading to the possibility of Type 1 errors and loss of information regarding important interrelationships among the dependent variables.

The above situation is surprising given the history of multivariate statistics, the extensive literature in the field and the availability of a number of "user-friendly" computer software packages such as SPSS$^{X}$ and BMDP. In some circumstances the multivariate statistical methods may be inappropriate due to the particular nature of the problem or the data. These circumstances might include inadequate sample size (low subject-to-variable ratio), failure of the data to satisfy multivariate assumptions or the lack of a multivariate technique for a specific research situation. However, Schutz et al. (1983) believed that researchers in the field have had little exposure to multivariate statistical techniques and that awareness and understanding of those techniques and their application needs to be promoted in the exercise and sports science fields.

One of the first multivariate analyses of rowing ability was conducted by Hay (1968) who utilized a multiple regression technique on 42 performance, physiological, anthropometric and experience variables. The variables included heart rate, stroke rate and work output data from a 6 minute rowing ergometer test, as well as anthropometric measures and strength and experience data. The summed ranks of five expert rowing judges were used as the criterion for the regression analysis. Although the strength, experience and anthropometric data did not contribute significantly to prediction of rowing ability, a combination of two heart rate measures, two stroke rate measures and the total work output measure did produce a strong prediction value ($\underline{R}$=.914).

Williams (1975) employed a stepwise multiple discriminant function analysis to examine personality differences between four different categories of 230 oarsmen. The author found that certain personality variables distinguished the experienced proficient oarsmen from the younger, less proficient and less experienced oarsmen.

A series of stepwise multiple discriminant function analyses were conducted by Williams (1977) on a battery of physiological, performance, anthropometric and psychological variables in order to discriminate between junior (under 19 years), colt (under 23 years) and senior (open) oarsmen. A second analysis was conducted between selected and non-selected oarsmen within each age group. The analyses were conducted on separate sub-sets of variables and their combinations. As expected, the model did not differentiate between the three age groups except for certain age-related factors, for example, body weight, biceps and calf girth measures, mesomorphy ranking and total flywheel revolutions. The analysis between the successful and unsuccessful trialists indicated that such differentiation was facilitated by the combined use of biological and psychological variables. This combination of variables was called the psychobiological dimension and the major discriminators between selected and non-selected oarsmen on this dimension were certain psychological and anthropometric variables. The psychological factors included I (tough-minded versus tender-minded), H (shy versus venturesome), M (practical versus imaginative), $Q_1$ (conservative versus experimenting) and C (emotionally less stable versus emotionally stable). The anthropometric factors included the bone diameters, knee width and elbow width, and the degree of mesomorphy. The psychobiological model determined for the senior rowers was 55% accurate in predicting junior selections and 83% accurate in predicting junior rejections. These figures represented a gain of 27% and 11% in prediction rates for selection and rejection respectively. The same analysis conducted for colts rowers produced overall prediction rates of 50% and 72% for selection and rejection respectively. These figures represented gains of 14% and 8% over the base rates for selection and rejection respectively. The findings of this study indicated the value of a multivariate approach in assessing the combined contributions of different kinds of information to the identification of those factors related to rowing success.

Williams (1978) conducted a stepwise multiple regression analysis utilizing a number of physical, physiological and psychological variables in order to assess which variables provided the strongest prediction of rowing ability for colts-level (under 23 years) oarsmen. Heart rate, work output and stroke rate data were obtained from a 6 minute rowing ergometer test. Anthropometric data provided body type and back and leg strength parameters while Cattell's 16 Personality Factor questionnaire provided psychological data.

The stepwise multiple regression analysis showed that 8 of the 62 variables were able to provide a strong relationship ($\underline{R}$=.837) with the criterion of rowing ability as judged by five experienced coaches. The eight variables were measures of total strength, heart rate and work output during the last 30 seconds of the ergometer effort and five personality variables. Once again, the author drew attention to the importance of using a combination of physiological, physical and psychological variables in order to predict high-level rowing ability.

The above review not only indicates the lack of multivariate research in rowing, but also reflects the predominant interest in the physiological aspects of rowing performance. If it can be shown that selected biomechanical performance variables can effectively discriminate between groups of rowers then a case can be made for the inclusion of biomechanical performance variables in multivariate analyses used to predict rowing ability. Having determined the relative importance of biomechanical performance variables to rowing performance, consideration must be given to the use of this information in the coaching process. The teacher/coach and/or sport scientist needs to consider the extent to which selected biomechanical performance variables may be modified to improve rowing performance. Also of importance is the mode and timing of the presentation of this information to individual rowers.

For the purposes of this study it was hypothesized that propulsive work consistency would be the least effective discriminator between groups of rowers despite the fact that the literature (Edwards, 1963; Klavora, 1982b; Pannel, 1972; 1979) strongly supports a high level of work consistency. It was decided therefore, to determine if propulsive work consistency could be improved via the visual presentation of augmented concurrent information feedback. This procedure served to examine the effectiveness of kinetic information feedback during maximal work.

## Information feedback in motor skill performance

While there are many factors that contribute to motor learning and performance, one of the most important is feedback. Numerous investigators (Adams and Goetz, 1973; Ammons, 1956; Baker and Young, 1960; Bilodeau, 1969; Bilodeau and Bilodeau, 1961; Fitts, 1964; Robb, 1968) have reported the beneficial effects of feedback on motor skill acquisition and performance. Higgins (1972; 1977) pointed out that consistency of movement and goal attainment are the hallmarks of effective skill acquisition and that research clearly indicated the key role of feedback in controlling human movement for goal attainment purposes (Adams, 1971; Annett, 1969; Gentile, 1972; Singer, 1980; Schmidt, 1982). In summary, feedback allows the learner to:

(1) Attend to proper cues.

(2) Receive information that may not be otherwise available.

(3) Attend to information that is available but may not be otherwise processed (Barbarich, 1980).

During the learning of a motor skill, it is necessary for the performer to match actions with progress towards goal attainment. Gentile (1972) believed that in order to do this, the performer must attend to certain regulatory cues that provide important information about the spatial/ temporal variability of the external environment or the temporal variability of the movement itself. Under these conditions, feedback is seen as facilitating goal attainment and consistency of movement by matching movement demands with environmental conditions (Higgins, 1972; 1977). As the performer practises the task, the nature of the task changes (Fleishman and Hempel, 1955) and with increasing task mastery the performer makes greater utilization of kinesthetic and proprioceptive cues (Beitel, 1980; Fleishman and Rich, 1963).

### Types of feedback

Feedback may take a number of forms namely external or internal, intrinsic or augmented, and terminal or concurrent. External feedback is not ordinarily present in the task and may be present as verbal information or as an external stimulus that is received through vision, touch, hearing or a combination of these senses. Proprioceptive and interoceptive feedback is inherent in the task. Feedback received during action is known as concurrent feedback whilst information received after action is called terminal feedback. Augmented feedback is additional information provided to supplement the feedback normally available during completion of the task (Dukelow, 1979; Sage, 1984; Schmidt, 1988).

Early research into augmented feedback was prompted by a desire to improve targeting skills for military purposes (Newell, 1981). However the extensive use, by physical education teachers and sports coaches, of a variety of verbal, visual or manual augmented feedback techniques led to considerable research into the use of augmented feedback for motor skill instruction (Adams, 1971; Adams et al. 1972; Dukelow, 1979; Gentile, 1972; Higgins, 1972; Malina, 1969; Robb, 1968; Rothstein and Arnold, 1976).

### Knowledge of results and knowledge of performance

Augmented feedback may be divided into two further categories, that is, knowledge of results and knowledge of performance. Both forms of feedback are classified as augmented terminal feedback, however, they may be presented as augmented concurrent feedback (den Brinker, Stabler, Whiting, and van Wieringen, 1986; Kerr, 1982; Sanderson, 1985a; Newell and Walter, 1981). Knowledge of results is feedback related to the extent to which an intended goal has been achieved and is the traditional form of information feedback for the learning and performance of motor skills (Kerr, 1982; Newell et al. 1985b; Sage, 1984). The information provided by knowledge of results is processed to allow for adjustments to the action plan so that performance level will improve on succeeding trials. The time of presentation and the nature of the knowledge of results significantly influences the rate of skill learning and the final performance level (Newell et al. 1985a).

Knowledge of performance is feedback related to the movement pattern itself, that is, the temporal, spatial, sequential or force aspects of the movement (Annett, 1969; Sage, 1984). It has been suggested that knowledge of performance is the more influential form of feedback for the stable, closed skill environment where the performer is attempting to consistently reproduce the most efficient movement pattern or where it is necessary to match a required movement pattern as occurs in sports activities such as high board diving, gymnastics and figure skating (Carre, 1972; Del Rey, 1971; Gentile, 1972; Hampton, 1970; Newell and Walter, 1981; Stewart, 1980; Thompson, 1969; Wallace and Hagler, 1979). On the other hand, knowledge of results might be the most effective form of feedback for the open skill environment where a variety of motor responses are required (Barbarich, 1980; Beitel and Ferguson, 1981; Newell and Walter, 1981). In certain circumstances, knowledge of performance may be of value in the acquisition of open motor skills given that the performance of open skills still requires a degree of movement consistency albeit within certain environmental constraints (Newell and Walter, 1981).

There is some evidence to suggest that knowledge of results and knowledge of performance are superior in combination to either individual feedback mode for both open and closed motor skills. This type of feedback is seen as focusing attention on correcting response selection and response execution errors, leading to more consistent movement patterns and more efficient performance (Beitel, 1983; Cooper and Rothstein, 1981; Gentile, 1972; Sage, 1984; Sanders, 1985).

There have been a number of claims (Fowler and Turvey, 1978; Gentile, 1972; Newell and Walter, 1981) that goal driven knowledge of results may be insufficient to maximize performance. It is believed that goal oriented knowledge of results does not provide sufficient information regarding the co-ordination and control functions of the body. Traditionally knowledge of results indicates what not to do rather than what to do on subsequent trials following an incorrect response (Fowler and Turvey, 1978).

Evidence in support of the use of knowledge of performance rather than knowledge of results for the learning of closed motor skills arises from the belief that performers attempt to develop a high level of kinematic consistency as they focus on task refinement (Newell and Walter, 1981). Knowledge of performance concerning kinematic parameters has usually been presented via videotape feedback. However, the skill level of the performer and the extent of verbal cueing has been shown to influence the effectiveness of this feedback mode.

Experienced performers benefit from unguided viewing of videotape feedback whilst novice performers require the assistance of verbal cueing. It ~~is~~ was proposed (Rothstein and Arnold, 1976) that videotape feedback be used as a supplement to verbal feedback so as not to overload performers with information at the earlier stages of motor skill acquisition.

It is apparent that the informational content of the feedback obtained from response dynamics is the essential element in determining the success of further action. However, Newell et al. (1983) suggested that the open-closed skill continuum did not provide sufficient information to allow determination of the appropriate augmented feedback despite the variety of motor responses possible, particularly in the open skill environment.

### Kinematic and kinetic parameters as information feedback

Augmented feedback of response dynamics in the form of kinematic or kinetic parameters related to the demands of the task, is seen as being more potent than traditional knowledge of results (McGinnis and Newell, 1982; Newell and Walter, 1981). The basis of this approach lies in the theory that the learning of motor skills involves mastery of redundant biomechanical degrees of freedom (Bernstein, 1967). In other words, the information feedback to be provided for the performer depends upon the complexity of the skill in terms of the number of joint actions which have to be constrained by the performer in order to achieve co-ordination and control of motor behaviour (Newell and Walter, 1981). Fowler and Turvey (1978) stated that the degrees of constraint provided by the information feedback should match the degrees of biomechanical freedom requiring constraint.

The effectiveness of knowledge of results feedback has been shown to depend upon the level of precision of the feedback and the time available to the performer for the processing of the information (Bilodeau, 1953; Newell and Walters, 1981; Rogers, 1974; Schumsky, 1965). However, these findings have been based on research utilizing tasks that were unidimensional in nature such as positioning, timing or accuracy tasks requiring only one biomechanical degree of freedom to be controlled by the performer. Traditional knowledge of results is a very effective form of feedback for such tasks because the outcome information is all that is required to constrain a single degree of freedom task. Knowledge of results is less useful in complex motor tasks involving multidimensional criteria in combination with one or more biomechanical degrees of freedom (Newell and Walter, 1981). For these tasks, information regarding degrees of constraint should be provided via kinematic and kinetic parameters with the particular number and type of parameters being task dependent (Newell et al. 1983).

When compared with knowledge of results and videotape replay, certain arguments may be advanced in favour of kinematic and kinetic information feedback in motor skill learning and performance. As previously mentioned, the level of precision of knowledge of results significantly influences the rate of motor skill acquisition. Any decrease in knowledge of results precision through reductions in the absolute accuracy or extreme transformation of feedback data has a deleterious effect upon the rate of 'learning'. It follows that the feedback presented to the performer should represent as closely as possible the actual movement pattern produced by the performer. While presenting an accurate representation of generated action, photographic and videotape techniques may not effectively identify and/or quantify the essential movement characteristics of a motor task. Despite recent advances in photographic and videotape technology, inter-response intervals are still too long, thus reducing the rate of motor skill acquisition.

The use of kinematic or kinetic parameters as information feedback may reduce or eliminate the need for information transformations and may assist the performer to selectively attend to relevant cues by reducing unnecessary response information (Newell and Walter, 1981).

The use of biomechanical performance variables (forces, joint or limb kinetics and muscular activity) for augmented feedback purposes in the performance of a complex motor task has attracted limited research interest. Sanderson (1986a) stated that the complexity of sports skills, the difficulties involved in identifying movements that are examinable, and the instrumentation required restrict the recording and feedback of relevant kinematic or kinetic data. There is also some concern as to whether already established movement patterns can be significantly modified. Despite the above limitations, the available research indicates the value of kinematic and kinetic parameters as information feedback.

## The effectiveness of kinematic and kinetic information feedback

Kinetic information feedback was used by English (1942) to teach rifle shooting to army recruits. This study was based upon the premise that the rifle stock should be squeezed simultaneously with the trigger in order to develop a smooth, slow trigger pull which in turn would positively influence target accuracy. Utilizing a modified rifle stock, the recruits initially received concurrent feedback on the amount of force applied to the stock. Following each shot, the recruits received terminal feedback regarding the amount of force applied to the stock compared with a criterion force generated during the performance of an expert marksman. The author reported significant improvement in shooting accuracy amongst recruits whose previous progress had been less than satisfactory.

Kinetic information feedback in the form of ground reaction force-time curves was used by Howell (1956) to modify force patterns during sprint starting. Subjects receiving traditional technique instruction were compared to those who received a force-time graph of their sprint start response. The subjects were required to match a theoretically optimal force-time curve for the sprint start that necessitated attaining peak force as soon as possible whilst simultaneously maintaining a maximal level of peak force. The subjects who received the kinetic information feedback reduced the difference between the criterion impulse curve and their self generated curves significantly more than the subjects who received conventional feedback.

The value of kinematic parameters as information feedback for the learning of simple motor skills was clearly shown by Hatze (1976). A single subject was required to raise one leg with a 10 kilogram mass attached, as rapidly as possible through a designated amplitude of 40 degrees. Knowledge of results in the form of task completion time was made available for the first 120 trials. When performance gains reached asymptote, knowledge of results was replaced by kinematic information feedback in the form of position-time curves generated by the hip and knee joints. These curves were superimposed on a computer-derived optimal position-time curve. Immediate reductions in movement time occurred and continued to do so over 100 trials with the final measures closely approaching the optimal criteria predicted by the author. The kinematic information feedback had a significant impact upon performance at a time when the benefits of knowledge of results had largely been realized and thus served to fine tune action at the advanced practice stage (Newell, 1981).

Lionvale (1977) utilized auditory presentation of concurrent kinematic feedback in the teaching of the fly fishing cast. The kinematic concurrent feedback took the form of a sound representing the rate of change of displacement of the elbow during a fly fishing cast. The subjects were required to match a criterion sound generated by the casting action of a champion fly caster. The fly casting action is essentially a short duration ballistic response, therefore, the information feedback could only effectively influence performance on the next trial. While the results were not statistically significant, improved fly casting performance was exhibited by those subjects who received concurrent auditory kinematic information feedback in comparison to control group subjects who were denied kinematic information feedback.

Kinematic and kinetic information feedback in the form of non-auditory displays of selected speech parameters has been utilized in speech instruction for the deaf (Stevens et al. 1975). Miniature accelerometers attached to the nose and throat were used to obtain wave form feedback of the glottal acoustic output and the extent of acoustic coupling to the nasal cavities. It was determined (Nickerson, Kalikow and Stevens, 1976) that the information feedback was instrumental in improving a number of speech parameters including timing, velar control and pitch control. The lack of improvement in intelligible unrehearsed speech was considered to be a function of the level of refinement of the non-auditory feedback displays. However, Newell and Walter (1981) believed that the relationship between kinematic and kinetic information parameters and response outcome may be more ambiguous for speech production than for other motor skills thus reducing the effectiveness of these forms of information feedback for speech development.

While the research conducted by English (1942), Howell (1956) and Hatze (1976) indicated the value of kinematic and kinetic parameters as information feedback, Newell and Walter (1981) stated that it would be necessary to identify specific situations wherein these alternative forms of information feedback may be applied. The pivotal concern in this process is the determination of the informational content of the kinematic or kinetic feedback and the manner in which this information interacts with the nature of the task and the performer's skill level (Newell and Walter, 1981). A number of studies have been undertaken to examine the proposal that the appropriate information feedback for motor skill learning is determined by the task criterion. That is, that the information feedback should match the degree of constraint influencing the response output (McGinnis and Newell, 1982).

Newell et al. (1983) conducted two experiments in order to contrast the influence of traditional knowledge of results with various kinematic feedback parameters during the acquisition of a single degree of freedom response necessitating movement time minimization over movement amplitudes of 15 degrees, 30 degrees and 45 degrees. In the initial experiment, the subjects received discrete information knowledge of results regarding peak acceleration, time to peak acceleration and final target velocity. It was hypothesized that the use of discrete kinematic parameters as information feedback may serve to overcome the constraints imposed by short amplitude movements. The parameters ~~are~~ were not superior to movement-time knowledge of results in minimizing the duration of a single degree of freedom rapid arm movement. However, the second experiment utilized continuous velocity-time information as terminal information feedback, the hypothesis being that the provision of information feedback in the form of a kinematic trace may allow the performer to develop the optimal kinematics necessary to achieve the task criterion. The results showed that this type of information feedback does facilitate movement-time performance with the subjects using the augmented information feedback to produce a kinematic trace with a higher optimization level than possible via the utilization of discrete kinematic parameters or outcome knowledge of results.

The relative effectiveness of traditional goal oriented knowledge of results and continuous kinetic terminal information feedback was examined by Newell et al. (1985b) in a study consisting of two experiments. Subjects in the first experiment were required to produce a criterion force during a simple isometric task. Two feedback groups were contrasted with one group receiving traditional goal oriented knowledge of results while the other group received continuous force-time traces of the generated impulse. The results of this experiment demonstrated that the provision of continuous force-time feedback did not improve the accuracy of peak force production or influence the manner in which the criterion force was achieved.

The task criterion was changed for the second experiment with the subjects being required to produce an impulse that exactly matched the shape of a gaussian-like force-time curve template with a peak force of 30 newtons and an impulse duration of 300 milliseconds. Three groups of subjects participated in this experiment. One group received continuous force-time feedback and was contrasted with groups that received terminal knowledge of results related to either the actual size of the generated impulse or, the absolute impulse-area error. It was hypothesized that discrete kinetic knowledge of results would provide insufficient information to minimize error when compared with continuous force-time information feedback. The feedback group that received continuous force-time information matched the criterion force-time curve template more accurately than the groups provided with discrete kinetic knowledge of results.

The results of the four experiments conducted by Newell et al. (1983; 1985b) support the proposition that the task criterion specifies the nature of the information feedback in that the information feedback must match the task constraints (McGinnis and Newell, 1982). It is apparent that kinematic and kinetic information can be used to improve performance given that the task constraints are well understood and that the information feedback "matches the constraints imposed on the optimal kinematic or kinetic trajectory" (Newell et al. 1985a, p.252). For example, performance optimization in isometric tasks with a criterion force-time history may only be possible if continuous kinetic information feedback is provided. Interestingly, Newell et al. (1985b) believed that the effectiveness of this form of information feedback may be increased where the characteristics of the force-time criterion curve depart from those representing a gaussian-shaped force-time curve. Whatever the task, both researchers and performers need to restrict the information feedback "to a coherent unit which represents the movement criteria which need to be constrained in the execution of the skill" (Newell and Walter, 1981, p.250).

Newell and Carlton (1987) examined the extent to which the interaction of task and organismic constraints influenced the effectiveness of augmented information feedback on the acquisition of a given force-time profile in a finger press isometric task. This research was in response to the uncertainty regarding the relative impact of descriptive (representation of the response just produced) and prescriptive (representation of the criterion) information on the acquisition of skill (Newell et al. 1985b).

The first of two experiments found that an augmented continuous force-time trace was superior to impulse knowledge of results information in improving performance, however the concurrent display of the criterion impulse with the augmented information feedback did not lead to further improvement in performance. This result was expected as the criterion impulse was a familiar shape (a symmetrical gaussian curve) which the researchers supposed would provide unnecessary information when superimposed onto the force-time trace of the just-produced response.

The second experiment utilized an unfamiliar criterion force-time trace superimposed onto the response force-time trace. It was theorized that the subjects would not be able to utilize prior knowledge of the impulse criterion to constrain the response impulse. Prior knowledge was considered to be an organismic constraint. The results indicated that the presentation of task criterion information along with kinetic information feedback acted to improve performance. This led the authors to suggest that the extent to which kinetic information feedback and criterion information assist in the acquisition of skill in an isometric task is prescribed by the interaction of task and organismic constraints. Therefore, the constraints that are apparent in the performance situation determine the appropriate augmented information feedback. Along with the addition of organismic constraints, this study supported the previous findings of Fowler and Turvey (1978), Newell et al. (1985b), and Newell et al. (1983). As stated by Newell (1986) constraints not only determine the ideal pattern of coordination and control but they also determine the information required by the performer in actual or simulated learning situations.

The very limited research on the use of biomechanical variables as information feedback during the performance of complex "multidimensional" motor skills provides support for the considerations stated above. Den Brinker and van Hekken (1982) used biomechanical variables as augmented feedback for subjects learning to make slalom type ski movements on a skiing simulator. Improved performance in terms of frequency, amplitude or fluency of movement resulted. In a later extension of this study, den Brinker et al. (1985) required the subjects to attend to one of the performance parameters with augmented feedback being provided on that parameter only. The results indicated that the subjects achieved the best results on those parameters to which their attention was directed and about which they received information feedback. However, when the data was analyzed over all of the training days, the group which received information feedback concerning amplitude of movement was the most proficient on all three dependent variables, namely amplitude, frequency and fluency of movement. Emphasis on the frequency of movement was found to limit amplitude maximization whilst directed attention to fluency of movement restricted movement frequency. Thus the provision of biomechanical variables as information feedback served to isolate the fundamental movement strategies necessary for the learning of gross motor (cyclical) skills.

Angst (1984) used concurrent visual feedback of the force-time curve to co-ordinate the interaction between the leg drive and the work of the upper body during the rowing stroke. Following an on-water pretest, 10 rowers undertook 10 training sessions in a still water rowing tank, conducted in 2 week cycles over a period of 6 months. The training sessions were of 15 minutes duration with work intervals of 70 seconds interspersed with rest intervals of 20 seconds. A monitor placed in the field of vision enabled the rowers to view the force-time curve for each stroke. On-water force coupling faults were also apparent in the training tank environment thus providing a sound basis for generalizability of the results. Improvements in force coupling technique were apparent from the first training session for all subjects and were shown to be readily transferable from the stable environment of the still water rowing tank to the on-water situation.

Komor and Leonardi (1988) stated that control of human movement is effected via a closed-loop feedback system wherein the performer acting in an "on-line" mode and the coach acting in an "off-line" mode, together constitute a co-ordinated control system. However, it was suggested that the visual analysis techniques utilized by the rowing coach and the proprioceptive feedback available to the rower are not precise enough for performance enhancement, particularly in the early stages of skill practice. The authors suggested an additional control system for the rower and coach involving computer-aided real time feedback of selected performance parameters. In this instance, a computerized rowing ergometer was used to provide feedback on rowing performance including peak pull force, stroke time, time of pull, time of peak pull force, peak pull force impulse, stroke regularity and the extent to which the derived pattern of force application matches an optimum pattern. It was determined that the provision of feedback in this manner was effective in improving individual rowing technique, particularly in regularizing the rowing action, and in selecting crew members. It appears that the comparison of pull force shapes and parameters was conducted posttest, using data samples from the beginning (1 minute), middle (3 minutes) and end of the test (6 or 7 minutes).

Concurrent visual feedback of the pattern of force application and pedalling rate was used by Sanderson (1986a) to modify the recovery phase pedalling mechanics of eight inexperienced cyclists pedalling at a steady rate of 60 revolutions per minute and a power output of 112 watts. Forces applied to the pedal during the recovery phase were manipulated in an attempt to reduce forces applied in a direction that was opposite to the crank rotation and thus counterproductive. Downward-directed forces applied during the recovery phase result in some of the force applied during the propulsion phase being used to overcome the counterproductive force produced by the opposite leg. The subjects pedalled for 32 minutes each day over a 10 day period with a control group ($\underline{n}$=4) receiving feedback on their pedalling rate only, whilst an experimental group ($\underline{n}$=4) received information feedback concerning their pattern of force application as well as pedalling rate. The information feedback consisted of a computer generated graphics image which showed a single vertical bar representing the average mean force during a 90 degree segment of the recovery phase averaged for each leg. The amplitude of the vertical bar was determined by the amplitude of the mean force generated by the left and right legs. It was determined that performance of this complex cycling task could be modified by information feedback of a biomechanical nature. The experimental group achieved lower forces more rapidly than the control group while reduced pedal forces in the recovery phase led to reduced pedal forces in the propulsive phase which prompted the author to speculate on the possibility of improved cycling economy.

Concurrent feedback of the torque generated during cycling was used by McLean and La Fortune (1988) in an attempt to reduce the incidence of negative torque in the recovery phase and thus improve pedalling efficiency. Subject (N=6) underwent two steady state cycle ergometer tests (90 revolutions per minute and 235 watts) of 15 minutes duration. Following the first test, subjects were shown a graphical display of the force acting on the right-hand crank arm over 30-32 pedal cycles obtained during the test. Subjects were shown the extent of negative torque in their pedal cycle and were instructed to attempt to lower the intensity and extent of negative torque during the second test and, if possible, generate positive torque throughout the pedal cycle.

During the second test, the subjects received continuous feedback of the torque characteristics of the crank arm. The biomechanical parameters obtained from the data included maximum and minimum torque, the extent of positive and negative torque, and a pedalling torque index which described the relative occurrence of positive and negative torque during the pedal cycle. The results indicated that the biomechanical feedback was effective in improving pedalling technique as demonstrated by a significant ($p<.05$) increase in the pedalling torque index. This finding suggested that at the same power output, less positive torque was ~~is~~ necessary during the downstroke to check negative torque generated by the limb during its upstroke. There was a trend towards lower peak positive and negative torque and reduced duration of negative torque. None of the subjects were able to exclude negative torque from the pedal cycle. As the subjects were highly trained cyclists, it was considered likely that they were not able to significantly vary their learned pedalling technique.

Scheduling of biomechanical feedback was utilized by Broker et al. (1989) to examine the proposal that continuous feedback may hinder learning by stimulating dependency on the feedback. Inexperienced cyclists (N=18) undertook 50 one-minute practice trials (78 revolutions per minute and 125 watts) on a stationary racing cycle and received biomechanical feedback of right pedal shear force and a criterion pattern emphasizing "effective" shear at 0 and 180 degrees. The subjects received either immediate or summary feedback. The immediate feedback consisted of concurrent feedback 140 milliseconds after every other pedal cycle while summary feedback involved the provision of averaged data between trials. All subjects performed 10 retention trials without feedback one week later whilst five immediate feedback and three summary feedback subjects undertook 10 additional retention trials and 10 dual task retention tests (counting backwards out loud) 2 months later.

Both groups of subjects improved significantly on all aspects of pattern deviation from the criterion with dramatic improvement in the early stages of practice and minimal gains in the latter stages. The one-week and two-month retention tests indicated minimal performance deterioration for both groups. However, the inclusion of a dual task did reduce performance. There was a tendency for the immediate feedback group to perform better on all pattern deviation measures during both practice and the one-week retention test. Group differences in the two-month retention test were measure dependent and insignificant. The results indicated that the provision of concurrent feedback did not have a negative influence on the learning of a continuous task. It was concluded that concurrent or time-averaged feedback can enhance cycling performance and that learned movement patterns are retained when feedback is removed.

Information feedback of a biomechanical nature has also been used in the development and assessment of muscular strength. Khalil, Asfour, Waly, Rosomoff and Rosomoff (1987) examined the effects of EMG biofeedback and kinetic information feedback namely force, on isometric strength gains. Force information feedback was provided via a digital display of the force exerted by the subject. Subjects who received both EMG and force information feedback displayed greater isometric strength gains than did subjects who performed the isometric exercise without information feedback. Force information feedback was seen as being motivational or a form of control over the neuromuscular loop similar to that postulated for EMG biofeedback. Force information feedback was determined to be an easier concept for subjects to understand and more appropriate for strength training in both clinical and sports training environments.

The motivational effects of information feedback during strength measurement was examined by Dworak (1987) who quantified the influence of information feedback on the level of strength of the elbow flexors and knee extensors in trained and untrained subjects. Both verbal and visual information feedback was found to significantly influence explosive torque of the knee extensors and elbow flexors as well as the torque generated by the knee extensors at any time. Information feedback had less effect on the strength of the upper extremity muscles indicating that the value of information feedback during strength assessment increases with the muscle mass being examined.

Information feedback of kinematic and kinetic parameters has been used in the allied health field where electromyographic techniques have been used to assist stroke patients to relearn motor control (Johnson and Garton, 1973). Warren and Lehmann (1975) utilized an auditory signal emanating from an insole pressure sensor to modify weight bearing during gait. Hull (1982) found that the use of continuous concurrent visual feedback via an oscilloscope facilitated the learning of force production techniques while Piggot (1982) determined that concurrent visual feedback was more effective than verbal feedback for teaching force production skills as a mode of physiotherapy treatment.

While there is general consensus regarding the importance of augmented feedback for motor skill acquisition and performance, there has been considerable debate as to the most effective feedback channel for movement guidance (Jordan, 1974; Klein, 1977; Klein and Posner, 1974; Smyth, 1978; Smyth and Marriott, 1982). Visual input tends to dominate other sensory modalities in a wide range of perceptual-motor activities. This dominance was seen by Posner, Nissen and Klein (1976) as being related to the relative ineffectiveness of visual inputs in informing the performer of their appearance. As a result of this reduced alerting capacity, attention was believed to be focused on the visual sense modality. That is, the attentional mechanism is biased towards the visual modality.

## The function of visual feedback

Visual feedback has been shown to facilitate response initiation and movement extent performance, particularly during the initial phases of motor learning (Adams, Gopher and Lintern, 1977; Christina and Anson, 1981; Newell and Chew, 1975; Posner et al. 1976). Pew (1966) found that as performers practised a task, they tended to shift from visual control of constituent movements to the use of visual input for intermittent amendment of the movement pattern. Fox and Levy (1969) stated that while proprioceptive cues may be inherently involved in motor tasks, they are often unable to affect successive improvements in motor performance. For improvements to occur, the authors recommended the use of external information feedback and in one of the earlier studies on action feedback, were able to demonstrate that line drawing responses guided by continuous visual feedback, were learned as well as with the more accepted terminal feedback. West (1967) examined the acquisition of typing skills under visual and non-visual input conditions. It was determined that kinesthetic feedback was used at a significantly lower level than all-senses feedback throughout the range of typing skill. The removal of visual input had no effect on typing speed but resulted in large and significant increases in errors. These findings suggested the utilization of visual inputs during the early stages of skill acquisition in typing as compared to the traditional "touch" procedure.

Posner et al. (1976) found that when information regarding an event was available from visual, auditory and proprioceptive sense modalities, attention was directed to the visual input providing that this input was adequate for response purposes. Adams et al. (1977) determined that when proprioceptive and visual feedback were presented simultaneously, that visual feedback was the more potent form. Stelmach and Kelso (1975) also provided evidence of the importance of visual information for motor behaviour. In situations where visual and proprioceptive information tends to be contradictory, the visual information is selectively attended to and the proprioceptive information is either dismissed or constrained (Lee and Lishman, 1975). Not surprisingly, Noback and Demarest (1967) were of the opinion that visual feedback was the most potent feedback channel given that movement responses were seen by the authors as being related to the mechanism of attention. Newell and Walter (1981) stated that one might intuitively conclude that a visual display is the best form of presentation of kinematic and kinetic information feedback even though, given the nature of the task, auditory or verbal presentations of response parameter(s) or dynamics might be more appropriate (Newell, 1976; Newell and Walter, 1981; Zelaznik, Shapiro and Newell, 1978).

Klein and Posner (1974) suggested that the presence of visual information and not the performer's intention to ignore or attend to it, ~~is~~ was the critical variable for kinesthetic reproductions. The availability of visual inputs was found to disturb the development of a kinesthetic pattern, however, the presence of kinesthetic inputs did not influence the attainment of a visual pattern unless the performer was directed to attend to the kinesthetic information. The processing of kinesthetic information was found to be affected by the presence of visual information regardless of whether the performer was attending to or attempting to ignore the visual information. The instigation of simple movements saw kinesthetic cues ignored in favour of visual cues even though this created some delay in the onset of movement. Attentional mechanisms were found to be important for the initiation and correction of discrete tasks while in continuous tracking tasks, expected corrections were believed to command more attention than unexpected corrections. These findings indicated a bias to attend selectively to visual inputs so that brief or weak stimuli were not missed.

Jordan (1974) found that performers who were asked to respond rapidly to simultaneous and redundant visual and kinesthetic inputs, tended to utilize visual input to shape their response, even though attention to kinesthetic input would have resulted in a faster response. Experiments conducted by Jones (1974) indicated that proprioceptive information is not entirely necessary for learning a movement and that there is little evidence that accuracy of movement control depends on proprioception. The author suggested that it was vision, and not prioprioceptive feedback, that instigated corrective adjustments by detecting discrepancies in fine discrimination.

Colavita (1974) analyzed conflict trials involving responses to visual and auditory stimuli that were presented simultaneously and found that visual stimuli were attended to before auditory stimuli. Smyth (1977) found that the simultaneous presentation of visual and kinesthetic feedback resulted in vision dominating attention to the extent that the kinesthetic trace was weakened and did not concur with the essential features of the task. Vision was found to define the size of a movement, even though it contradicted movement output and kinesthetic information. It was further suggested that the use of a visually controlled movement may help increase the preselected portion of the movement and therefore, following practice, the performer will depend to a lesser extent on visual feedback. A further study conducted by Smyth (1978) supported the findings of Posner et al. (1976) whereby the removal of visual response-produced feedback influenced both the generation and comprehension of movement. Visual guidance prevented performers from using kinesthetic information to gauge movement accuracy regardless of the relevance of the visual information.

Smyth and Marriott (1982) examined the role of articular proprioception and visual information in the performance of a simple catching task and found that visual information about the position of the hand is important for catching. Previously, theories of perceptual motor skill acquisition had indicated that visual control of the effectors is important in the early stages of learning but that as learning continues, the control of limb movements increasingly becomes the responsibility of proprioceptive rather than visual inputs (Gibbs, 1970) or that central preprogramming acts to reduce the need for continual visual control thus freeing vision to attend to other facets of the task (Keele, 1973). However, the results of this study indicated that proprioceptive information does not provide adequate detail about limb position and it was hypothesized that visual information serves to calibrate the proprioceptive system.

It would appear that visual feedback not only influences attention, but also the learning and retention of motor responses. Robb (1968) varied visual feedback to subjects performing a pursuit tracking task and found that those subjects who were provided with concurrent visual feedback performed with less error than subjects receiving periodic or no visual feedback. Adams et al. (1977) found that performance in acquisition and knowledge of results-withdrawal trials was optimal amongst subjects who received concurrent visual feedback and the most number of acquisition trials. For both high- and low-acquisition trials, the learning rate was most rapid for those subjects who received concurrent visual feedback. Christina and Anson (1981) found that visual feedback with knowledge of results enhanced consistency of performance early in learning and maintained movement extent performance during knowledge of results withdrawal. Visual feedback was seen as a positive influence on the retention level of the movement pattern.

Jones (1977) examined the effects of the quantity and location of visual feedback cues on a gross motor task (the long jump) and found that there was an optimal level of feedback precision for learning. Subjects who received the greatest amount of feedback performed poorly indicating a lack of time to process the quantity of information presented, as Rogers (1974) had earlier suggested.

The role of concurrent visual feedback in the observational learning of a normally unobservable novel action pattern was investigated by Carrol and Bandura (1982). Subjects were required to enact a modelled action pattern involving eight separate postures with specific movement characteristics between postures. Visual monitoring of movement reproductions were provided via an online videotape and occurred during early or late enactment periods, or not at all. The provision of visual feedback during performance was found to facilitate accurate reproduction of the modelled action pattern particularly, for the complex response components. It was determined that visual feedback did not facilitate performance in the early stage of learning the complex movement sequence reflecting insufficient cognitive representation of the sequence. This finding supported the social learning view held by authors that observationally-learned behaviours are cognitively depicted and that visual feedback enables the performer to reduce anomalies between conception and action. It was also found that the removal of the model and visual feedback did not adversely affect performance. Therefore, model effectiveness was seen as being related to the complexity of the task with visual feedback seen as having an important role at significant stages of learning.

Visual feedback may also be more useful to a skill if visual cues bear a one-to-one correspondence to the appropriate dimension of the movement itself. For example, in rowing this one-to-one relationship could be between a template of a desired force-angle profile shape and the stroke angle and resultant force of each stroke. As well as this, there may be more persistent effects of feedback in later stages of learning where the performer can evaluate the feedback more accurately (Newell, 1981).

Zelaznik, Hawkins and Kisselburgh (1983) stated that a prevalent belief was that concurrent visual feedback is sampled intermittently and then deciphered prior to visually-based corrections. The time taken to process the visual feedback was seen as supporting the control of movement by motor program theory (Schmidt, 1976). That is, if the processing of visual feedback takes more time than the actual movement then a motor program must have controlled the movement sequence. Visual feedback processing time had previously been estimated to be between 190 and 290 milliseconds (Beggs and Howarth, 1971; Keele and Posner, 1968) providing support for the motor program control theory for short duration movements. More recent research (Smith and Bowen, 1980) had indicated that visual feedback processing time may in fact, be less than 190 to 260 milliseconds and might well be below 100 milliseconds.

Zelaznik et al. (1983) found that visual feedback improved spatial accuracy for aiming movements that were less than 200 milliseconds in length. These findings suggested that Beggs and Howarth (1971) and Keele and Posner (1968) overestimated visual feedback processing time. One of the reasons suggested for this situation was the uncertainty of visual feedback presentation. It was proposed that if performers are aware that visual feedback is available, they will prepare to utilize it, on the other hand, visual feedback cannot be used by a performer if it is present but unexpected. The results of this study suggested that if motor program control is to be considered as a valid construct then it must allow for the utilization of visual feedback with very short time delays. Thus, rapid visual feedback processing serves to correct errors in the completion of motor programs.

Mulder and Hulstijn (1985) suggested that the use of artificial sensory feedback for example, force, may be more useful than "natural" feedback such as vision. However, it was proposed that if the acquisition of performance is directly related to the amount of feedback available, then the combination of force and visual feedback may be expected to cause a more significant increase than vision alone.

Edwards (1963, pp.52-53) stated that "of the five bodily senses, those of sight, hearing, and touch are very much used by the oarsman, and of these sight is by far the most important. Any oarsman who fails to use his eyes to the best advantage, is throwing away a priceless asset". In crewed boats rowers are encouraged to watch the rower in front in order to synchronize their movements. Also it is recommended that as the rower slows down prior to the "gather" on the stretcher (that is, prior to the catch) that occasional glances at the stroke's blade be taken to coordinate timing. It is also advocated that rowers take infrequent glances at their own blade in order to accurately assess the depth of blade entry (Edwards, 1963; Pannell, 1972).

In summary, visual input is seen as being largely conscious input whereas proprioceptive input reaches a lower level of consciousness (Granit, 1977). The colour, detail and depth sensitivity available from visual input provides quality control for movement that is not available from other sensory modalities (Adams et al. 1977). Also motor learning might be seen as a perceptual learning process (Gibson, 1969) whereby the discriminating characteristics of stimuli are discerned in the perceptual trace and affect motor behaviour. Visual feedback may be more effective than other sensory input mechanisms in focusing on and understanding the features of the perceptual trace. Kelso (1982) stated that vision is attended to naturally because it is the most reliable source of both concurrent and terminal information feedback, and because it allows activity to be planned more effectively. It may well be that visual information is of more benefit to certain tasks than it is to others. In short, visual information feedback can provide the performer with knowledge of the outcome of a movement and knowledge of how to prepare for future action.

## Summary

Despite the extensive history of competitive rowing, interest in the biomechanics of rowing is relatively recent. Interest in the science of rowing has traditionally focused on the physiology of rowing with

84.4% of the science of rowing literature surveyed for this study being devoted to this area, whilst only 8.3% of the literature was concerned with the biomechanics of rowing. While there is support for the biomechanics of rowing in the coaching literature there is little evidence of biomechanical information being used to identify limiting factors in rowing performance, to determine the best available technique for individual rowers or for determining race strategy.

Biomechanical analysis in rowing involves consideration of the kinematics and kinetics of the boat-oar-rower mechanical system. The kinematic parameters of rowing represent the overall "view" or "shape" of the motion and involve boat velocity (particularly fluctuations in boat velocity), stroke rate, length of slide, oar handle and oar blade trajectory, angular velocity and angular displacement of the oar, horizontal displacement and horizontal velocity of the rower's centre of gravity, and angular displacement and velocity of relevant body segments (knee, hip, arm, trunk, and lower leg angles).

A range of internal and external (kinetic) forces serve to influence these kinematic parameters and overall rowing performance, that is, final race time. The kinetic parameters influencing the boat include the inertial forces acting on the centre of gravity of the boat-oar-rower mechanical system and the fluctuation in hydrodynamic drag (both viscous and wave drag). Oar forces comprise the reaction force at the oarlock, force exerted on the handgrip, and the longitudinal and transverse components of the forces acting on the blade. The rower as an integral part of the mechanical system contributes kinetic parameters such as the inertial forces acting on the rower's centre of gravity, the forces exerted on the oar handle, reaction force on the seat, and reaction forces on the stretcher. The oar, as the main propulsive unit, has received the most research attention related to the kinetic analysis of rowing.

A number of different measurement techniques have been used in the analysis of the external forces acting on the oar. Earlier studies in this area were conducted for purely scientific purposes and utilized complex and inflexible technology to derive the required data. More recent studies have taken advantage of the considerable advances in computing technology, micro-electronics, and rowing simulator development, resulting in more accurate and readily translatable information for both coaches and sport scientists.

Oar force analysis, made possible by the above procedures, allows the coach to accurately determine what is occurring between the oar and the water. Traditionally, coaches have relied on the characteristics of the mound of water developed by blade pressure. While perhaps a useful field guide to rowing performance, the coach cannot accurately quantify or analyze the relationship between the rower's actions in the boat and what is happening between the oar and the water. That is, the effectiveness of the forces exerted by the rower, translated via the oar to the water, in propelling the boat forward.

Oar force analysis in rowing involves consideration of force-time, oar angle-time and force-oar angle parameters. Rowers have been found to possess highly individual force curves which can be used to assess rowing technique and to match or balance members of a crew. Cinegrams (stick figure representations of the rowing action) and hand curves (line curves of the path of the hands and the end of the oar handle during the rowing stroke) have been used for similar purposes but provide less objective information unless combined with force curve data. The use of force curve analysis for the assessment of rowing ability and capacity has traditionally been concerned with the force-time curve, which provides information concerning the rower's strength, stroke rate, the ratio of drive time to recovery time, force magnitude and the time taken to reach maximum force following the catch. The force-angle profile has largely been ignored, despite revealing a range of features of considerable importance to the evaluation of rowing capacity and skill. These features include stroke length, peak force, peak force position, inertial force, catch force, finish force, work output, stroke smoothness, stroke-to-stroke consistency and propulsive work consistency.

The limited research conducted on the force-angle profile has indicated that ergometer derived data on the shape of the profile and the magnitude of selected biomechanical parameters is similar to data measured in the boat. The assessment of work capacity for rowing has traditionally involved the evaluation of physiological responses to ergometer efforts of varying intensity, duration, and frequency. The rowing ergometer is the preferred work instrument due to specificity considerations. Also, recent research has indicated that a wheeled ergometer may be preferable to a stationary ergometer when simulation accuracy is considered.

One of the challenges of sports science research is the establishment of categories of competitive excellence for a particular sport. This process depends on the recognition of relevant performance variables and on the assessment of the combination and relative importance of these variables for high level performance. Previous multivariate research in rowing focused on the relative importance of a variety of performance, anthropometric, psychological and physiological variables. The utilization of biomechanical performance variables within this multivariate model would serve to assist in the identification of successful rowers. Having determined the relative importance of selected biomechanical performance variables to maximal rowing performance, it remains to determine how this information can be used in the coaching process.

It is widely accepted that feedback is one of the most important factors in the acquisition and performance of motor skills. Despite the existence of various theories of motor learning, confusion surrounding the validity of these theories and uncertainty concerning how information is used once it enters the human information processing "system", there is no doubt as to the value of feedback in the modification of motor behaviour. There are a number of different forms of feedback, namely, external or internal, intrinsic or augmented, and terminal or concurrent. Augmented feedback is externally provided information and is extensively used by physical education teachers and coaches to supplement information normally available during the performance of a motor task. Two important categories of augmented feedback are knowledge of results and knowledge of performance. Knowledge of results is augmented feedback related to the nature of the result produced in terms of the intended goal, while knowledge of performance is augmented feedback related to the characteristics of the movement pattern produced. Knowledge of performance is believed to be more effective in the closed skill environment where consistency and accurate criterion matching is important. Knowledge of results is believed to be the more effective form of feedback in the multi-response open skill environment. It is apparent that the success of intended actions is dependent upon the information provided by response feedback. However, the open-closed skill continuum may serve to limit augmented feedback choice while goal oriented feedback may not provide adequate information concerning control and coordination of bodily actions.

Augmented feedback in the form of task related kinematic and kinetic parameters may prove to be more effective that traditional feedback where complex motor tasks involving multidimensional criteria and one or more biomechanical degrees of freedom are involved. These alternative feedback modes are believed to provide a greater level of precision, more closely represent the movement pattern produced by the performer, lessen or eliminate the need for information transformation and may help to reduce unnecessary response information thus allowing the performer to focus on relevant cues. The provision of kinetic and kinematic information feedback is dependent upon recognition of the inherent complexity of sport skills, identification of measurable movement parameters and development of accurate instrumentation used in the recording and presentation of relevant feedback data.

A number of research studies support the use of kinematic and kinetic information feedback. English (1942) used force feedback during the trigger squeeze to teach rifle shooting. Howell (1956) used ground reaction force-time curves to maximize force output during sprint starting. Hatze (1976) used position-time curves generated by hip and knee joint movements as augmented feedback when performance gains from knowledge of results had been realized.

More recent research (McGinnis and Newell, 1982; Newell and Walter, 1981; Newell et al. 1983; 1985a; 1985b) examined the specific conditions under which these forms of information feedback may be applied. These studies indicated that kinematic and kinetic information feedback can be used to improve performance provided that the informational content of the feedback matches the task constraints, and that the interaction between the nature of the task and the performer's skill level is taken into account.

The use of biomechanical performance variables as information feedback has been shown to significantly influence the performance of complex "multidimensional" motor skills. Den Brinker and van Hekken (1982) and den Brinker et al. (1985) found that biomechanical variables used as augmented feedback assisted in the identification of the fundamental movement strategies necessary for simulated slalom skiing performance. Angst (1984) determined that computer-aided real-time feedback of selected biomechanical performance variables was effective in improving individual rowing technique. Sanderson (1986a) utilized concurrent visual information feedback of the pattern of force application and pedalling rate to modify the recovery phase pedalling mechanics of inexperienced cyclists. Continuous biomechanical feedback of the torque characteristics of the bicycle crank arm was found by McLean and La Fortune (1988) to significantly improve pedalling technique in highly trained cyclists. Scheduling of biomechanical feedback was examined by Broker et al. (1989) who found that concurrent for time-averaged feedback can improve cycling performance and that learned movement patterns are retained once feedback is removed.

Along with awareness of the informational content of the feedback, the nature of the task, the task constraints, and the skill level of the performer, there is a need to consider the appropriate mode of presentation of the augmented information feedback. All of the studies mentioned previously utilized visual feedback. Visual input has been shown to be the more potent form of feedback tending to dominate other sensory modalities across a wide range of perceptual-motor activities. Visual feedback has been shown to facilitate performance during the early stages of motor skill acquisition and, as skill acquisition progresses, the performer utilizes visual control for intermittent modification of the movement pattern and for calibration of the proprioceptive control mechanisms. The more experienced performer utilizes external information feedback to gauge successive improvements in motor performance that are not discernible via proprioceptive cues (Fox and Levy, 1969). Visual feedback has been shown to facilitate the accurate reproduction of complex modelled action patterns. Visual feedback may not be as effective in the early stages of learning, such actions reflecting insufficient cognitive representation of the action pattern (Carrol and Bandura, 1982; Jones, 1977). The greater capacity of the experienced performer to evaluate external information feedback may greatly increase its effectiveness. The fact that it is delivered via the most dominant sensory input modality ensures the importance of such feedback at all significant stages of learning (Carrol and Bandura, 1982; Newell, 1981). The attentional mechanism is biased so strongly towards visual input that one might conclude that kinematic or kinetic information is best presented visually even though, given the nature of the task, alternative modalities might be more appropriate (Newell and Walter, 1981). It has been suggested that selective visual attention and not proprioceptive information allows the performer to focus on brief or weak stimuli and to instigate corrective adjustments by detecting fine levels of variance in visual and proprioceptive inputs (Klein and Posner, 1974).

Visual feedback not only stimulates attention leading to enhanced consistency of performance during learning, but it also serves to influence the learning and retention of motor responses and enables the performer to recognize discrepancies between conceptualization and realization of the action plan (Adams et al. 1977; Carrol and Bandura, 1982; Christina and Anson, 1981). In order to maximize the effectiveness of visual feedback it may be necessary to ensure that it is analogous to the desired movement pattern, that the performer be made aware of its availability, that it be presented in a manner which facilitates rapid information processing and that the frequency of presentation allows for continuous assessment of the action plan (Newell, 1981; Zelaznik et al. 1983).

# Chapter 3

# METHOD

This study was conducted in two phases. Phase One involved the identification of a number of biomechanical performance variables which could be used in conjunction with work output to achieve accurate discrimination between rowers and to provide meaningful feedback for the rower and the coach. Phase Two involved the determination of the effects of increased propulsive work consistency on mean propulsive power output per kilogram of body mass during maximal ergometric rowing.

## Subjects

### Phase one

The subjects (N=41) involved in this facet of the study comprised 9 novice, 23 state and 9 national level male rowers. The majority of the subjects were from various rowing clubs in the Sydney region, however, 7 of the national level rowers were from interstate.

### Phase two

The subjects (N=34) were club level male rowers from various rowing clubs in the Sydney region. Descriptive statistics for both groups of subjects is presented in Table 1.

**Table 1**
**Descriptive characteristics of subjects**

| Subjects | | Age (yr) | Height (cm) | (MASS) Weight (kg) |
|---|---|---|---|---|
| Phase one | M | 21.8 | 182.9 | 78.9 |
| (N=41) | SD | 2.8 | 5.8 | 8.9 |
| Phase two | M | 21.6 | 181.6 | 79.5 |
| (N=34) | SD | 3.3 | 5.5 | 7.9 |

All subjects were required to give their informed consent (American College of Sports Medicine, 1989) (see Appendices A and B) and the current health status of each subject was determined prior to testing. The subjects were randomly assigned to a control (n=17) or experimental (n=17) group.

## Apparatus

The apparatus used in this study was based on an instrumented Repco rowing ergometer (model 907). The Repco rowing ergometer has been used by Australian rowing clubs for training and testing purposes and for rowing research (Leighton, 1983; Pyke et al. 1979; Spinks & Konkolowicz, 1985; Stuart, 1984). The Repco rowing ergometer is a portable type rowing machine. A fan is driven by applying a force to a handle representing the oar. The handle moves in a sweep motion as occurs in the boat. The fan is powered by a rope attached to the handle with the effort being transmitted via a set of pulleys and a spragg clutch. The fan resistance represents the frictional losses experienced by the moving boat (Leighton, 1983; Telford, 1980).

In order to more closely simulate actual rowing, certain modifications were made to the Repco rowing ergometer prior to instrumentation. Initially, the rowing ergometer was modified by the provision of wheels aligned to the ergometer's longitudinal axis (see Figure 17). As a result of this modification, the ergometer was free to move in a forward or backward direction in relation to the rower's movements on the slide.

It was also necessary to design a retaining bracket for the oar handle that would allow a closer simulation of the travel characteristics of the oar as well as allowing accurate measurement of the angle that the oar travels through (see Figure 18). The standard retaining ring allows for the former, but by nature of its construction, also allows an unacceptable amount of play in the angle rotated. The guide pin on the retaining bracket that inserts into the rigger was machined in order to minimize the play and allow for more accurate readings. This was achieved by designing a guidepin made from mild steel with a minimal amount of clearance. The guidepin was lubricated with Rocol MTS 1000 grease to maintain smooth rotation.

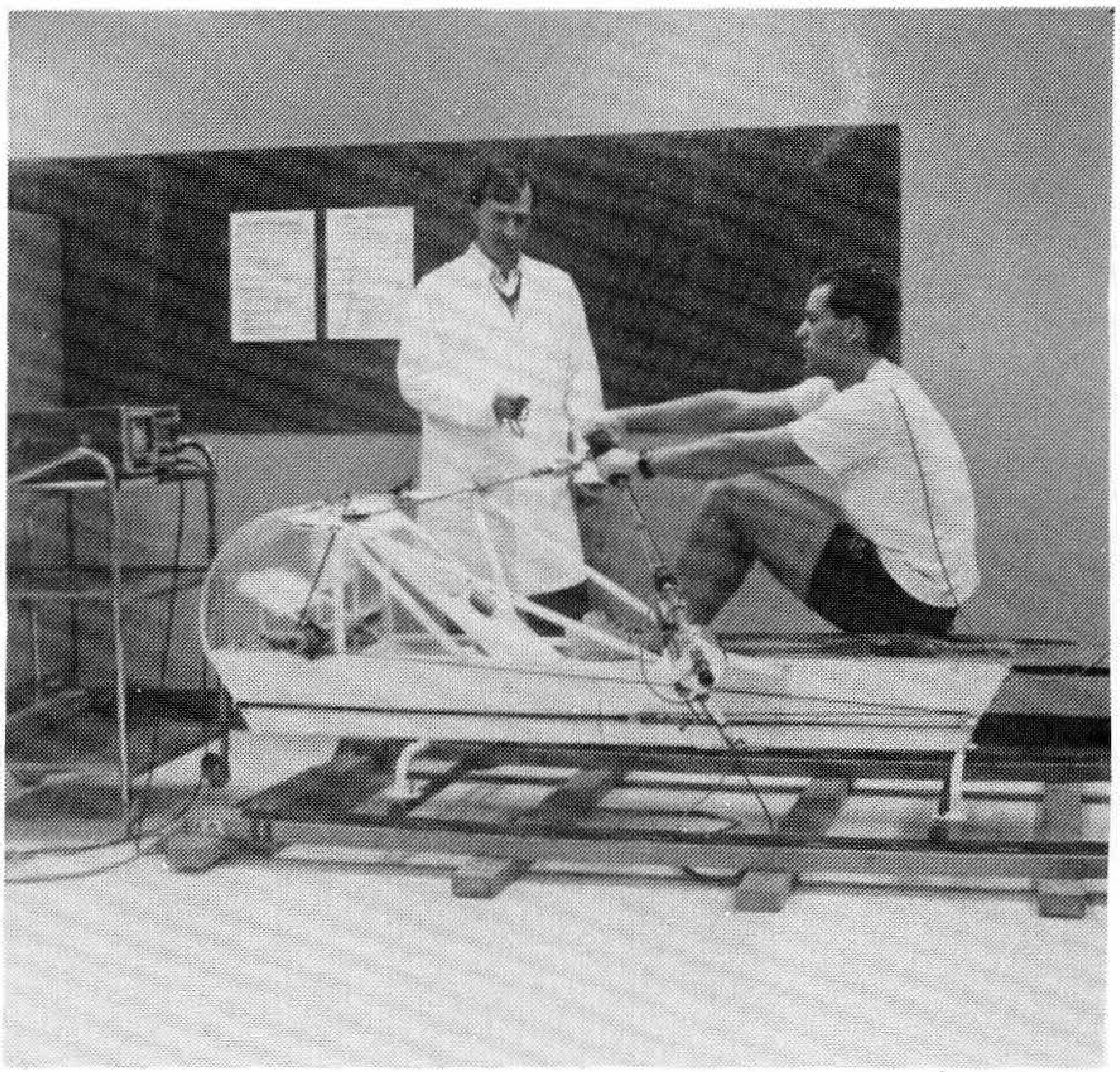


Figure 17 Wheeled Repco rowing ergometer

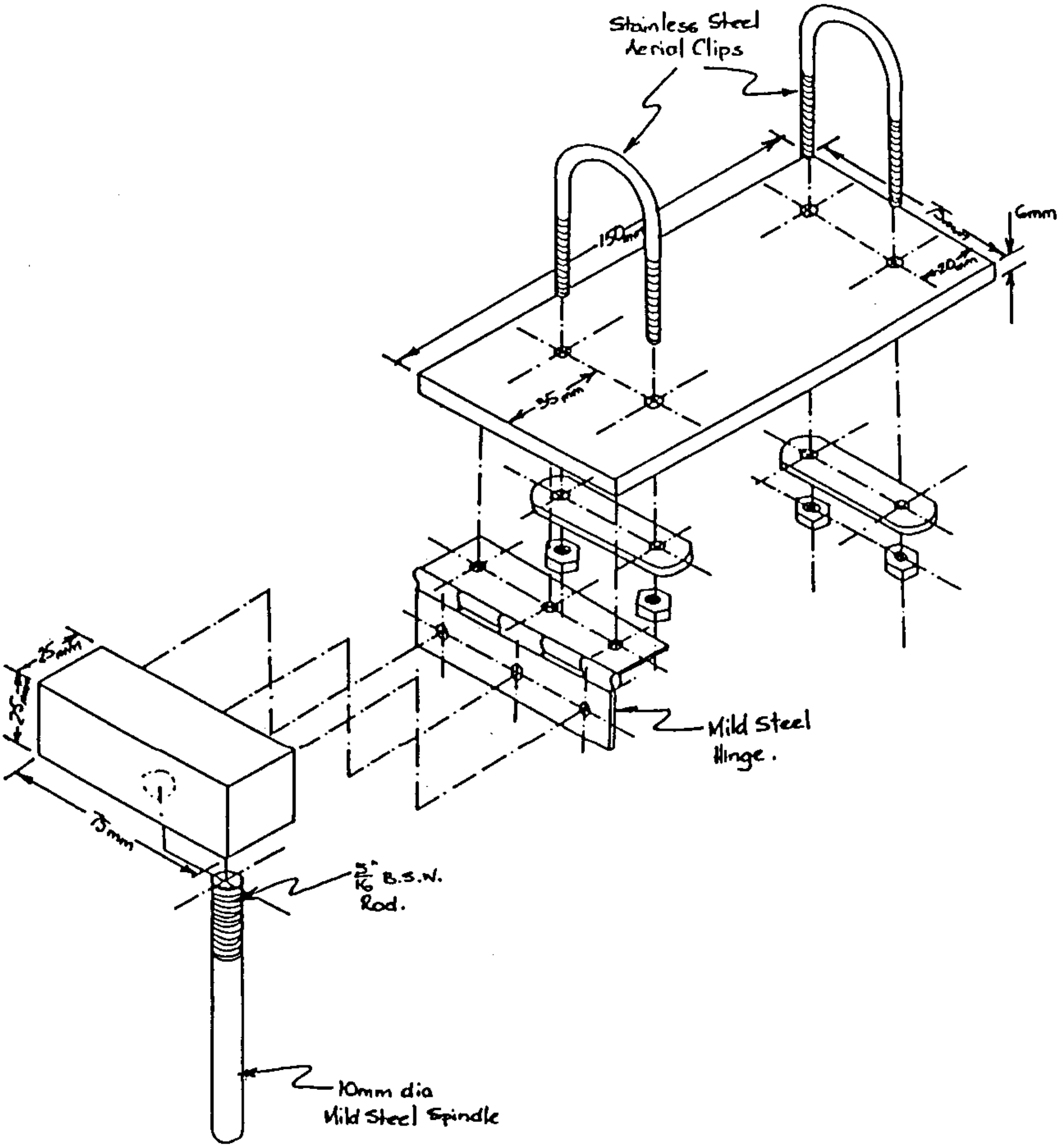


**Figure 18 Oar handle retaining bracket**

Oar force was determined via an XTRAN S1W 2KN S-beam load cell (Applied Measurement) attached in series with the rope of the rowing ergometer (see Figure 19). This transducer has a stated linearity of 0.03% and hysteresis of 0.02%. The load cell was connected to a RD-201A transducer readout (Applied Measurement). Calibration of the load cell was achieved by suspending a known mass (462.56 newtons) from the load cell (see Figure 20).

Oar angle data was measured using a 10 kilohm servo potentiometer (Radio Spares, 173-580) with a guaranteed linearity of 0.5%. The servo potentiometer was mounted on the guidepin of the oar pivot (see Figure 21). The power supply and signal conditioning unit utilized in the instrumentation comprised a LM 336 precision, temperature compensated, voltage reference integrated circuit (see Figure 22). Calibration was achieved by noting the oar angle at predetermined points on the body of the rowing ergometer in line with the travel path of the oar handle, that is, at minus 30 degrees, 0 degrees, and plus 30 degrees (see Figures 23, 24 and 25). The relationship between the ergometer rope angle and the ergometer oar angle was determined from the geometry of the ergometer as shown in Figure 26 and is described in the following equation:

$$\mathbf{Sin}\ \gamma = \frac{\mathbf{a\ sin}\ \beta}{\sqrt{\mathbf{a^2 + b^2 - 2ab\ cos}\ \theta}} \tag{6}$$

$$\mathbf{Torque} = \mathbf{T\ sin}\ \gamma\ \mathbf{.b}$$

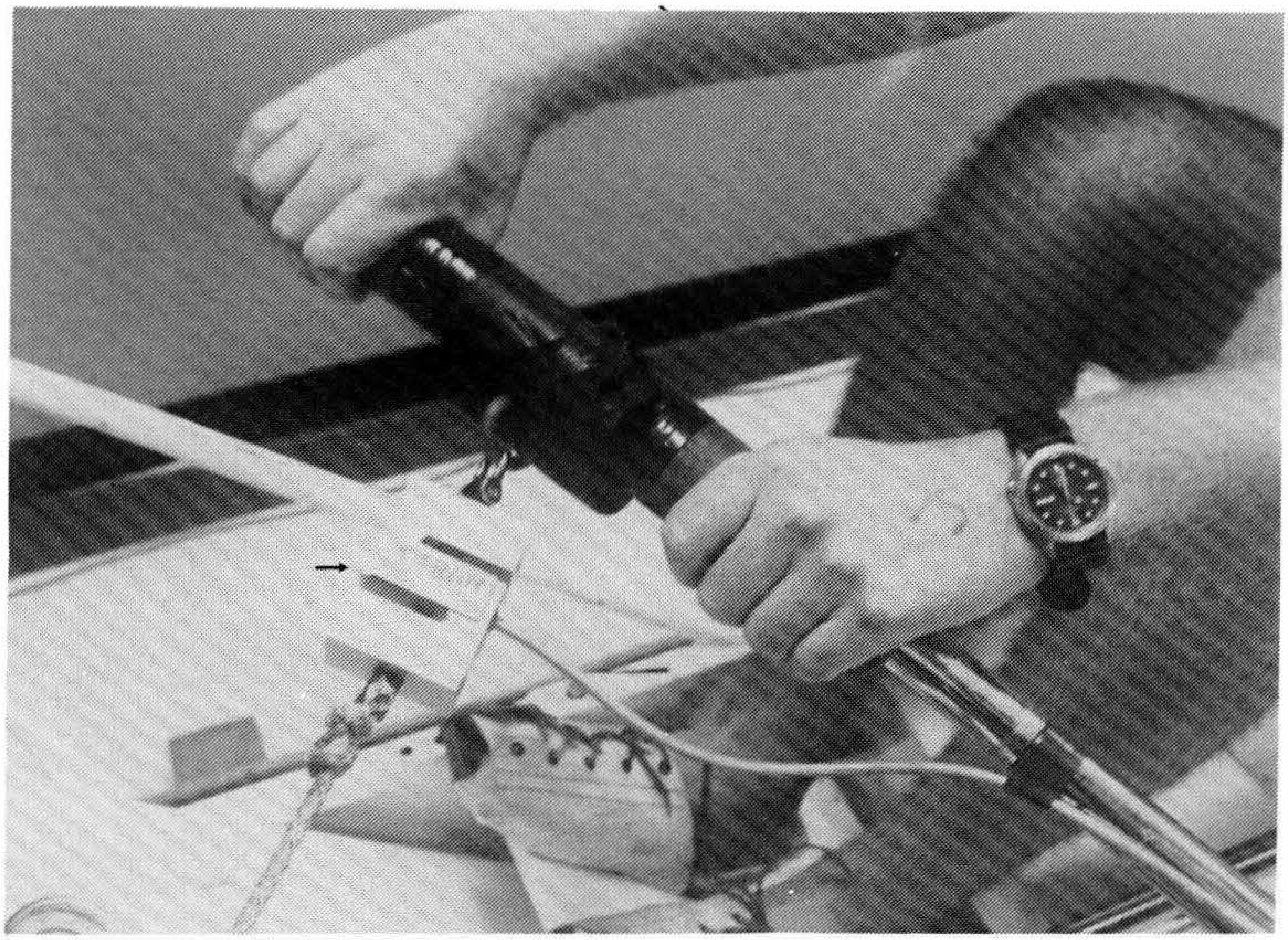


Figure 19 Load cell assessment of oar force

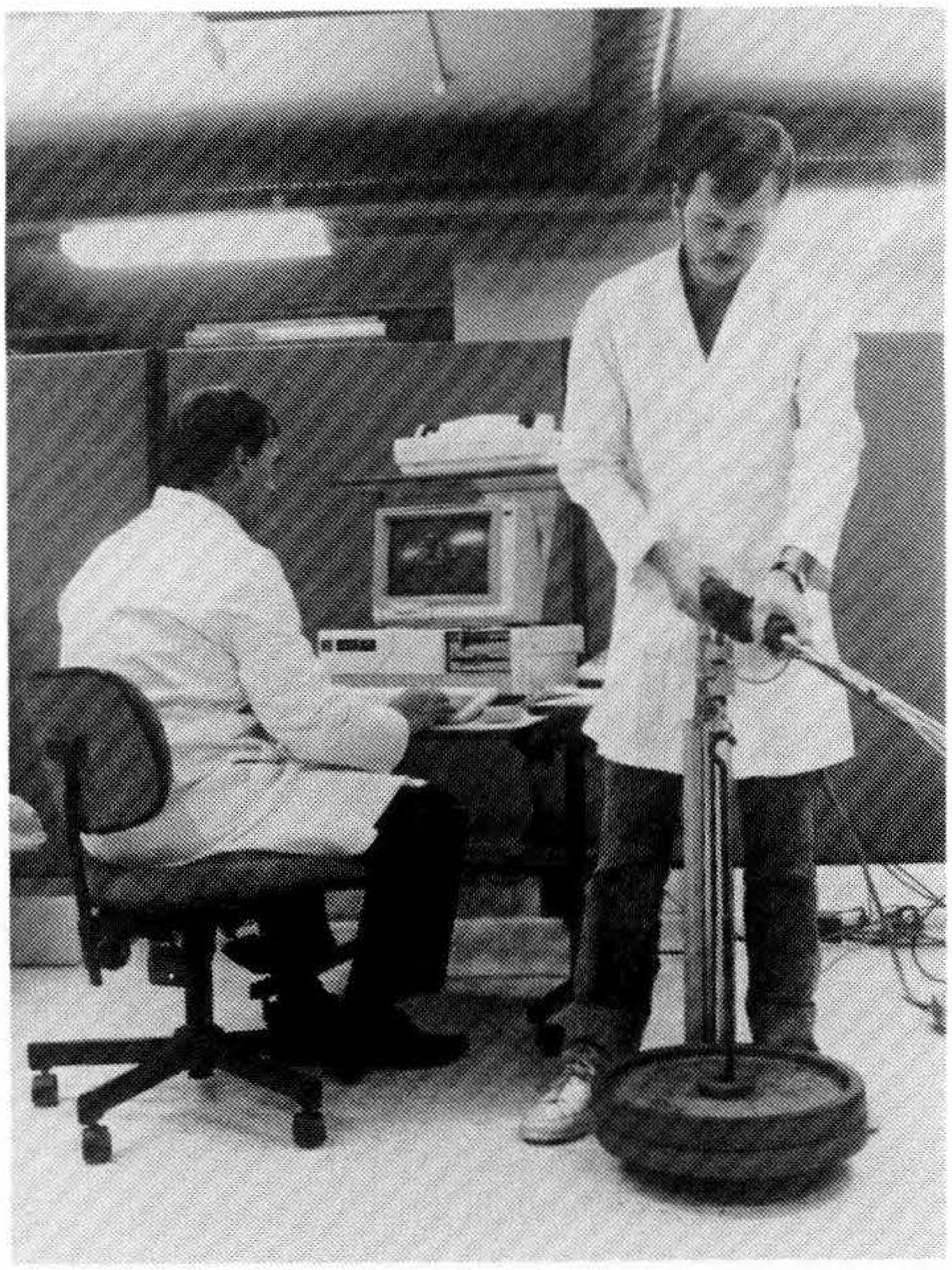


**Figure 20** Calibration of the load cell

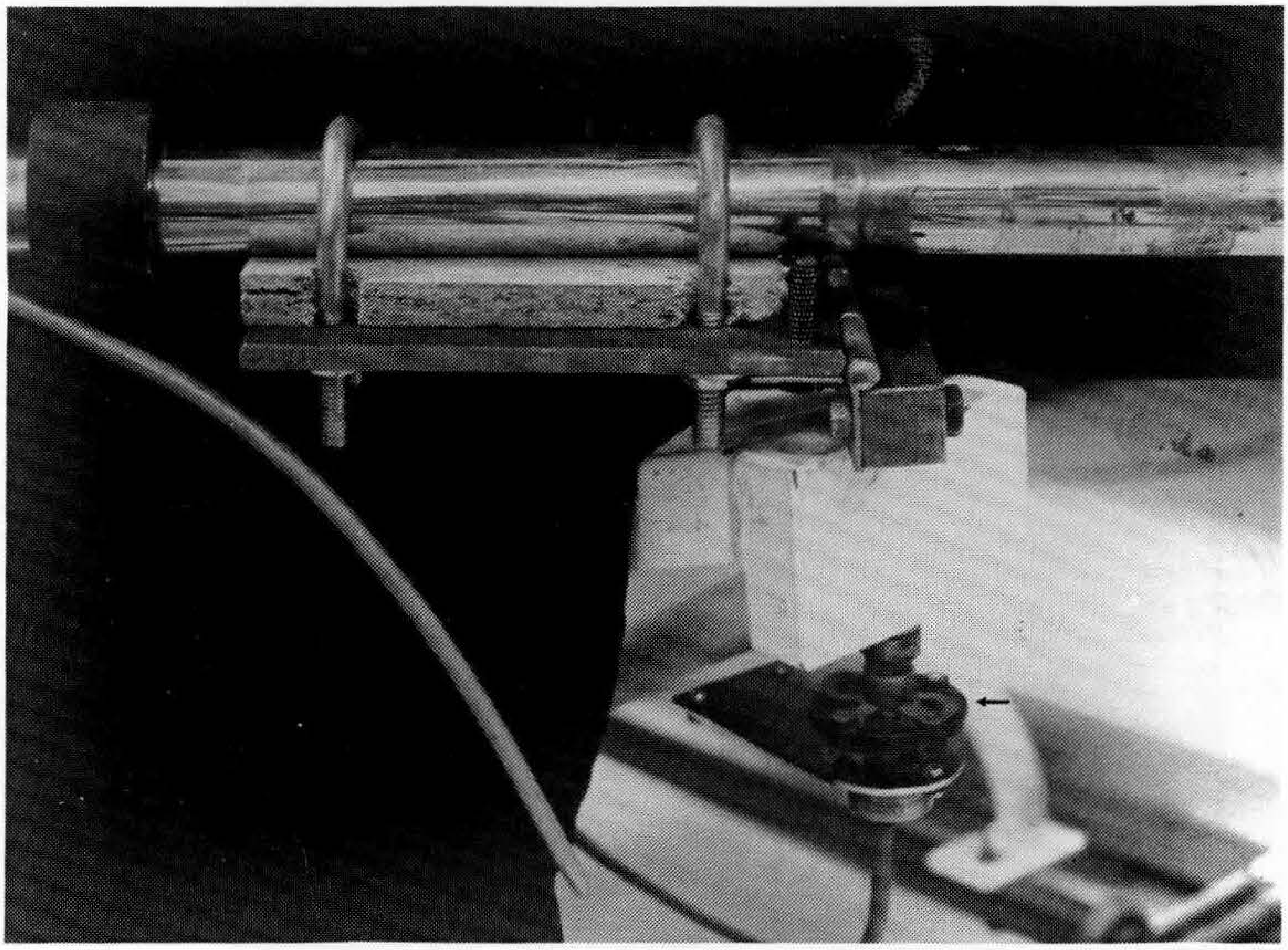


Figure 21 Servo potentiometer for oar angle assessment

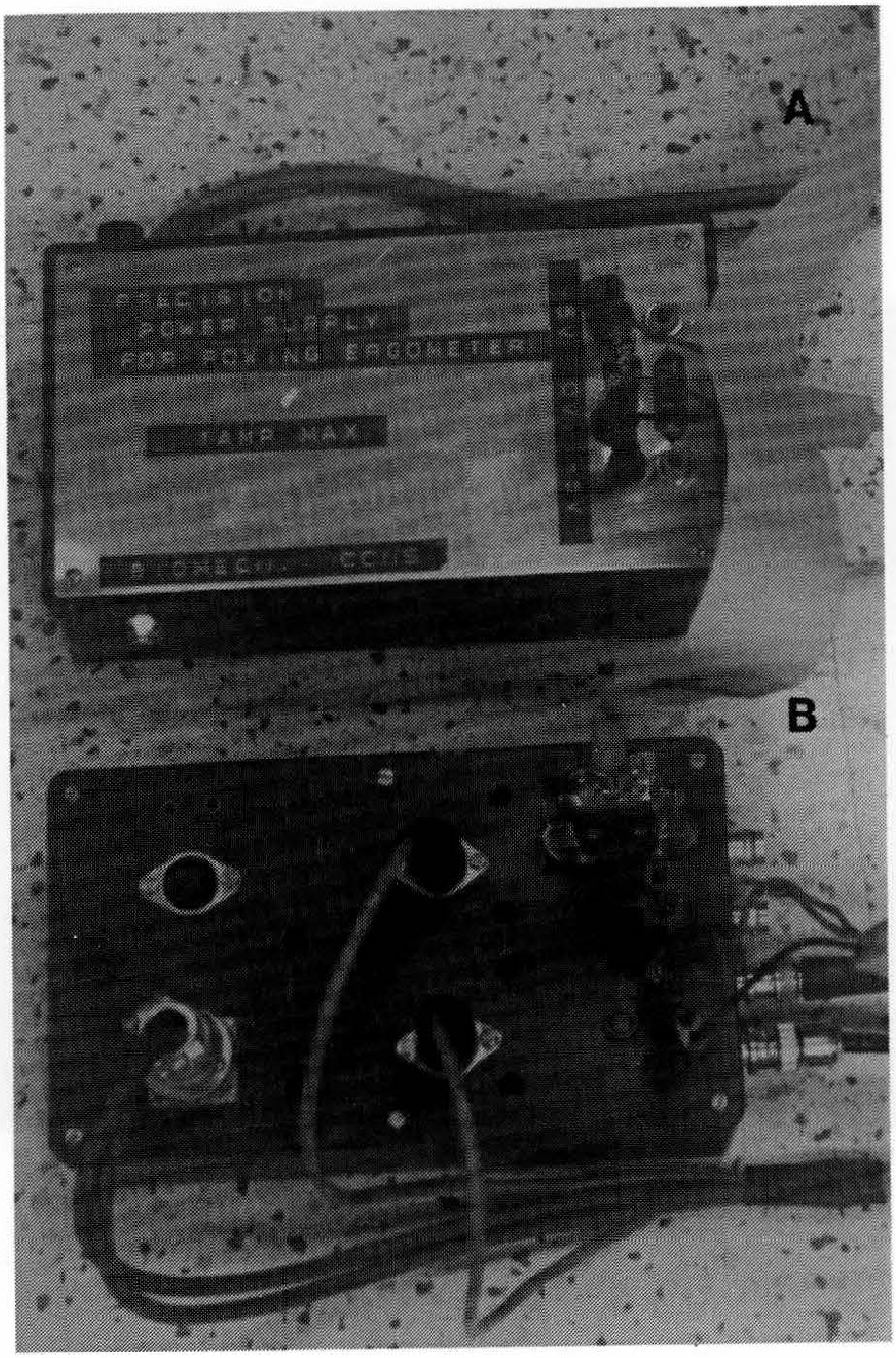


Figure 22 Precision power supply (A), and signal conditioning unit (B)

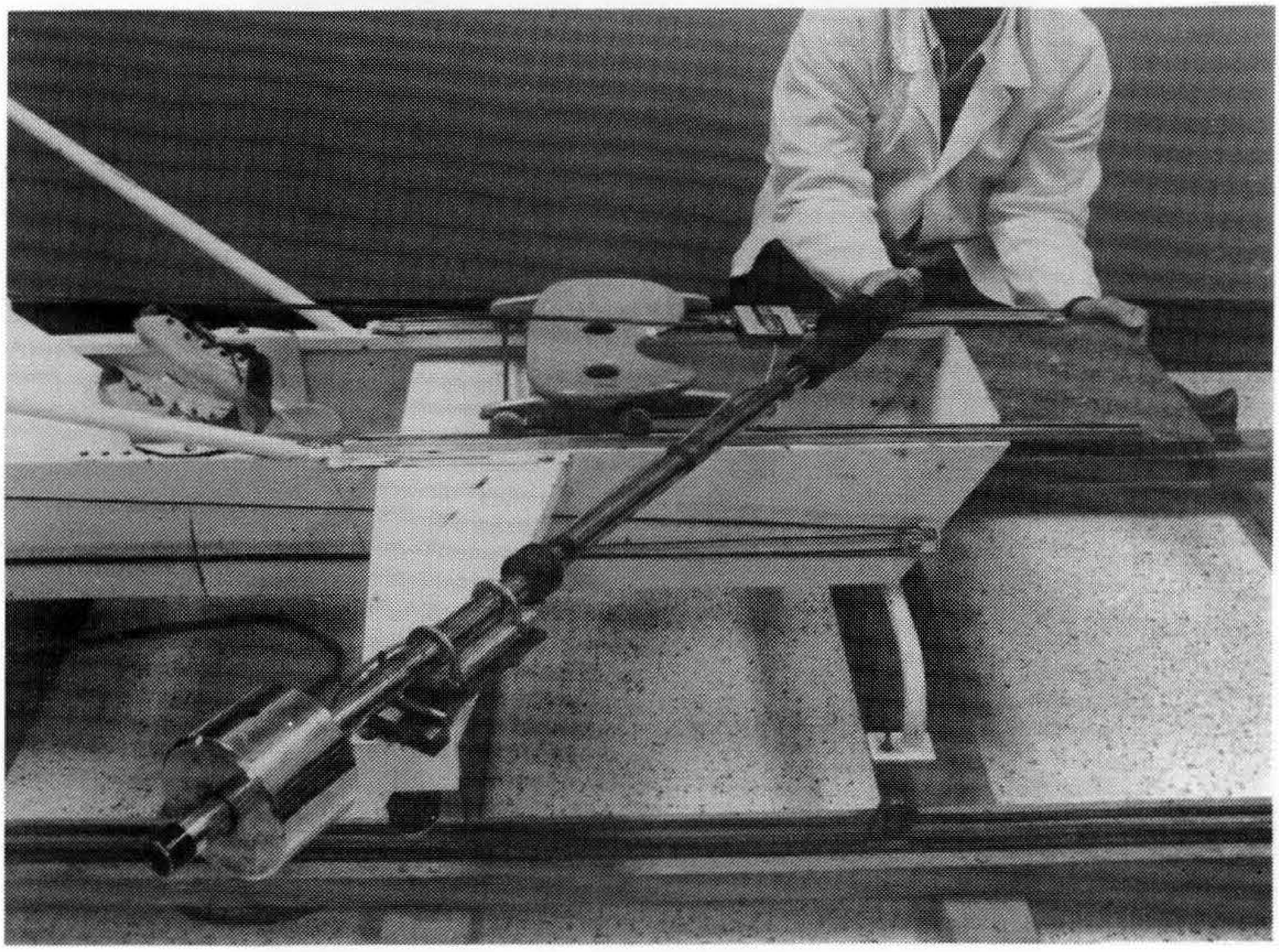


Figure 23 Oar angle calibration at minus 30 degrees (finish position)

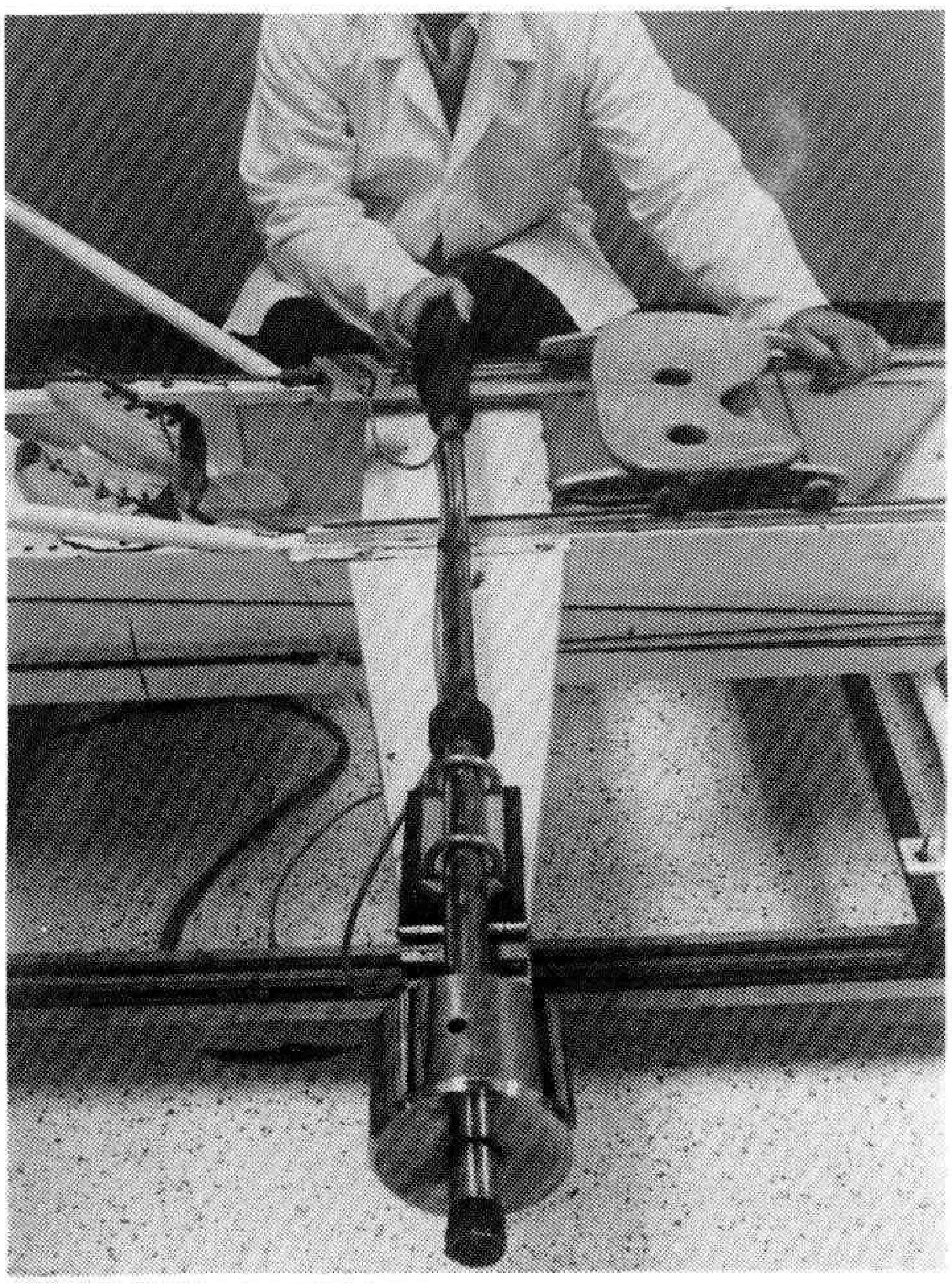


Figure 24 Oar angle calibration at zero degrees ("square-off" position)

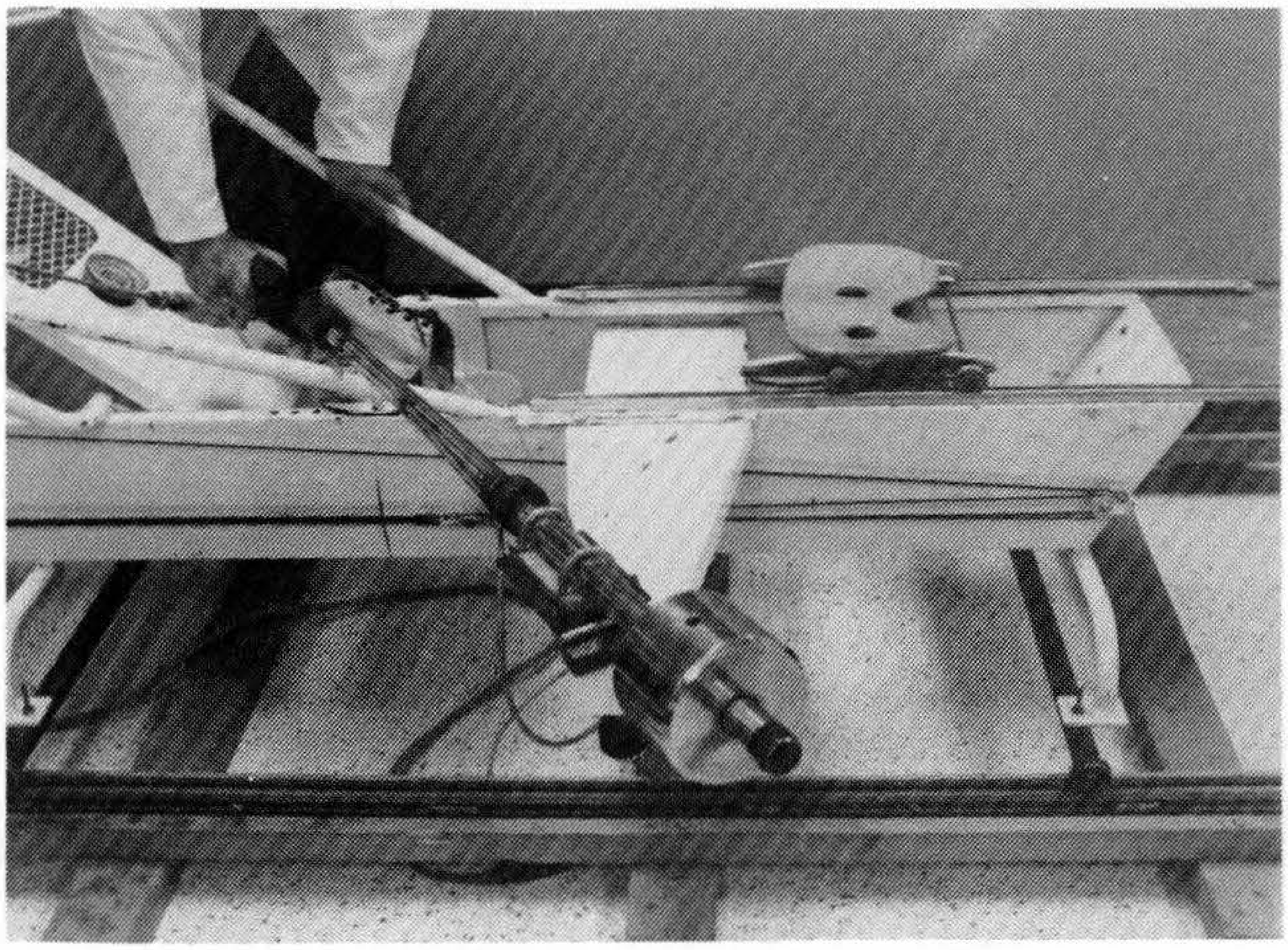


Figure 25   Oar angle calibration at plus 30 degrees (catch position)

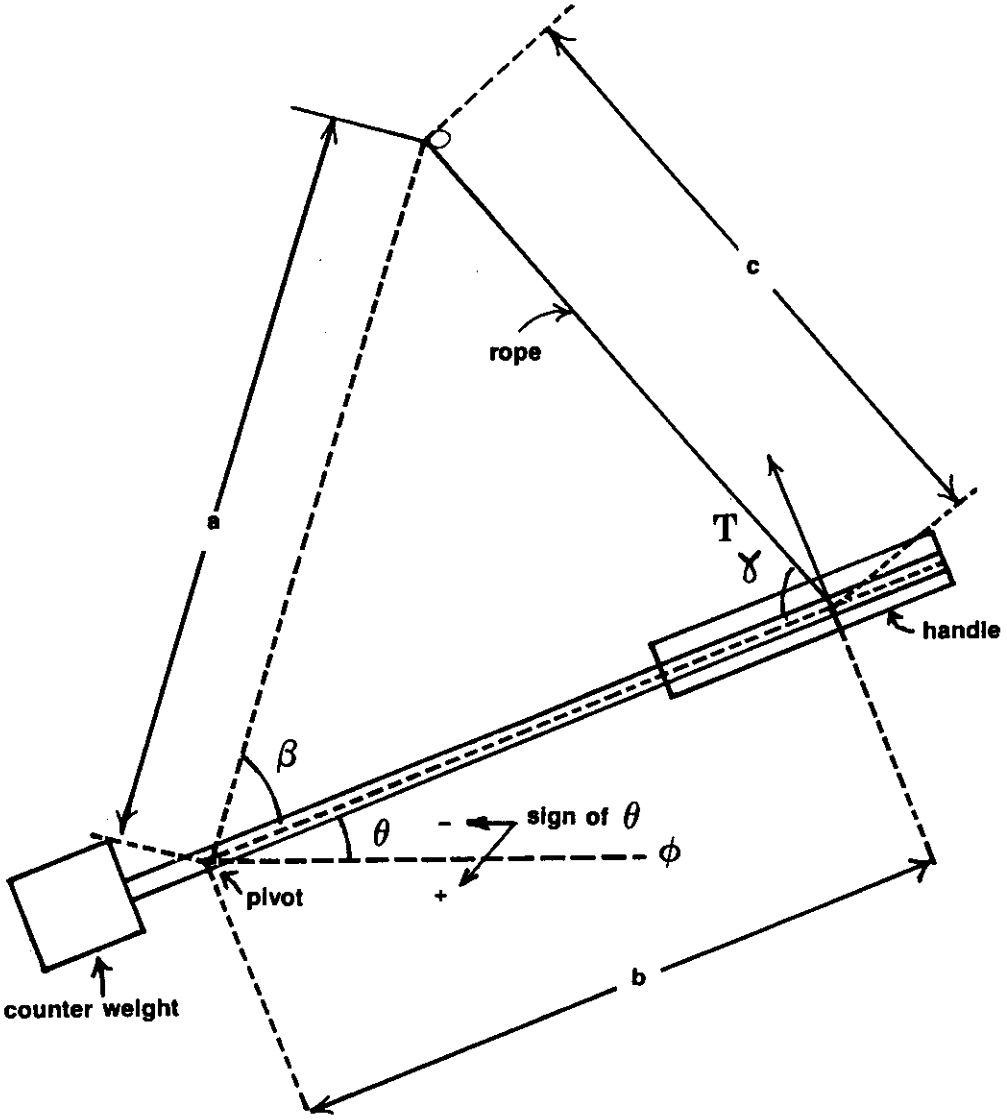


Figure 26   Determination of rope angle and oar angle relationship

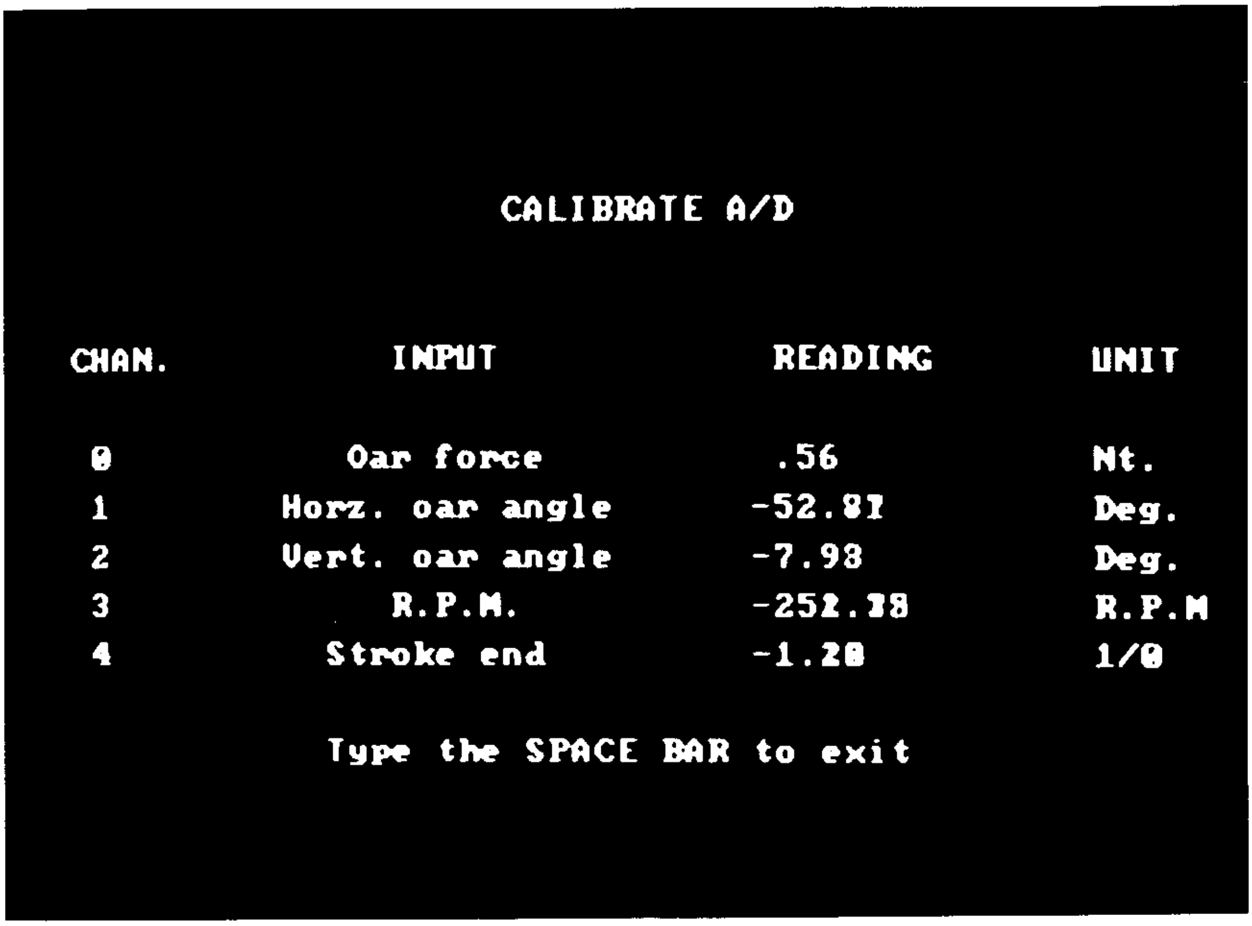
The calibration procedure was monitored on-line via an MS-DOS computer (see Figure 27). Collected force and angle data from a 6 minute maximal rowing ergometer test were filtered with a cutoff frequency of 12.5 hertz and sampled for an 8 second period every 30 seconds at 25 hertz via a DT2801 analogue to digital converter (Data Translation) and processed by an MS-DOS microcomputer. The data collection rate was determined given a maximum frequency of 5 hertz for the rowing movement (Martindale & Robertson, 1984).

The trapezoidal rule (Kaplan, 1952) was used to calculate the work done by the rower according to the following equation:

**Work done for interval ($W_e$) = (average torque for interval x change in angle)** (7)

Part of this work is dissipated in squeezing the side of the rowing ergometer in a direction perpendicular to the direction of motion (as is the case in the in-boat situation). Therefore, the trapezoidal rule was also utilized to determine the work done in the direction of motion, that is, propulsive work done ($PW_e$), viz.,

**Propulsive work done for interval ($PW_e$) = (average torque for interval x change in angle x cosine of angle)** (8)



```
                          CALIBRATE A/D

CHAN.          INPUT                READING        UNIT

 0           Oar force               .56           Nt.
 1        Horz. oar angle          -52.87          Deg.
 2        Vert. oar angle          -7.98           Deg.
 3             R.P.M.              -252.38         R.P.M
 4           Stroke end            -1.20           1/0

              Type the SPACE BAR to exit
```

Figure 27 On-line monitoring of calibration procedure

Propulsive work consistency (PWC) was measured by determining the coefficient of variation of the propulsive work ($PW_e$) for the 13 samples of work output,

$$\textbf{Propulsive work consistency (PWC)} = \textbf{100 (1 - coefficient of variation of } \mathbf{PW_e}\textbf{)} \tag{9}$$

Mean propulsive power output per kilogram of body weight (MPPO) was measured by taking into account the length of the stroke (degrees of sweep), the component of force applied in the direction of the motion of the ergometer, and the body mass of the rower, and was the averaged power output over the total period of the test,

$$\textbf{Mean propulsive power output per kilogram of body mass (MPPO)} = \frac{\textbf{total propulsive work}}{\textbf{360 x body weight}} \tag{10}$$

Mean stroke-to-stroke consistency (MSSC) was determined by normalising force data for each stroke with respect to time with the mean and standard deviation of the force values of each 2% of each stroke being calculated. The coefficient of variation for each 2% of each stroke was calculated as,

$$\textbf{Coefficient of variation for each 2\% of stroke} = \textbf{S.D./mean of force values for each stroke} \tag{11}$$

The consistency measure was then calculated as,

**Mean stroke-to-stroke consistency (within sample) (SSC) = 100 (1 - mean coefficient of variation)** **(12)**

The final measure of stroke-to-stroke consistency was determined as the grand mean of the 13 samples taken throughout the 6 minute test.

Stroke smoothness (SMO) was calculated by carrying out a fast fourier transform on a time normalised and reflected, averaged force data for each 30 second sample. The reflection was carried out to:

(1) Prevent anomalous harmonics due to the abrupt truncation of the data at the catch and finish phases of the stroke.

(2) Present one drive phase as a full cycle for easier interpretation of the fourier transform coefficients.

This was achieved by normalising the drive phase force data to 32 data points, taking the mirror image of the first 16 data points and adding it to the beginning of the drive phase, and then taking the mirror image of the last 16 data points and adding their mirror image to the end of the drive phase. The fourier transform was then conducted using these 64 data points. The amplitude of the fundamental was expressed as a percentage of the total amplitude of the first 10 harmonics on the assumption that a half sine wave is the ideal shape for a force-time curve. The mean of the 13 samples was presented as the mean smoothness value.

$$\text{Mean smoothness} = \left( \frac{\text{amplitude of the first harmonic}}{\text{total amplitudes of harmonics 1-10}} \right) \times 100 \qquad (13)$$

**(SMO)**

Processed data files for the 6 minute maximal rowing effort provided information on stroke rate (strokes per minute), length of stroke (degrees), peak force (newtons), work done (joules), propulsive work done (joules), stroke-to-stroke consistency (%), propulsive work consistency (%), stroke smoothness (%), mean propulsive power output per kilogram of body mass (watts), power/time and peak force/time graphs and average force-angle profile graphs for each 30 seconds of the maximal rowing test. A sample processed data file is presented in Appendix I. A schematic representation of the instrumentation system is presented in Figure 28. The computer program used to process the data was written (Smith and Turner, 1987) in ASYST (ASYST 2.0, 1987) and is outlined in Figure 29.

## Procedures

All measures necessary for this study were collected during test sessions conducted in the Biomechanics Laboratory, Cumberland College of Health Sciences, The University of Sydney.

### Phase one

All participating subjects were requested not to eat less than 3 hours prior to testing and were asked not to engage in any strenuous exercise in the 24 hours prior to a test session. Test sessions were conducted between the hours of 9 a.m. and 9 p.m.

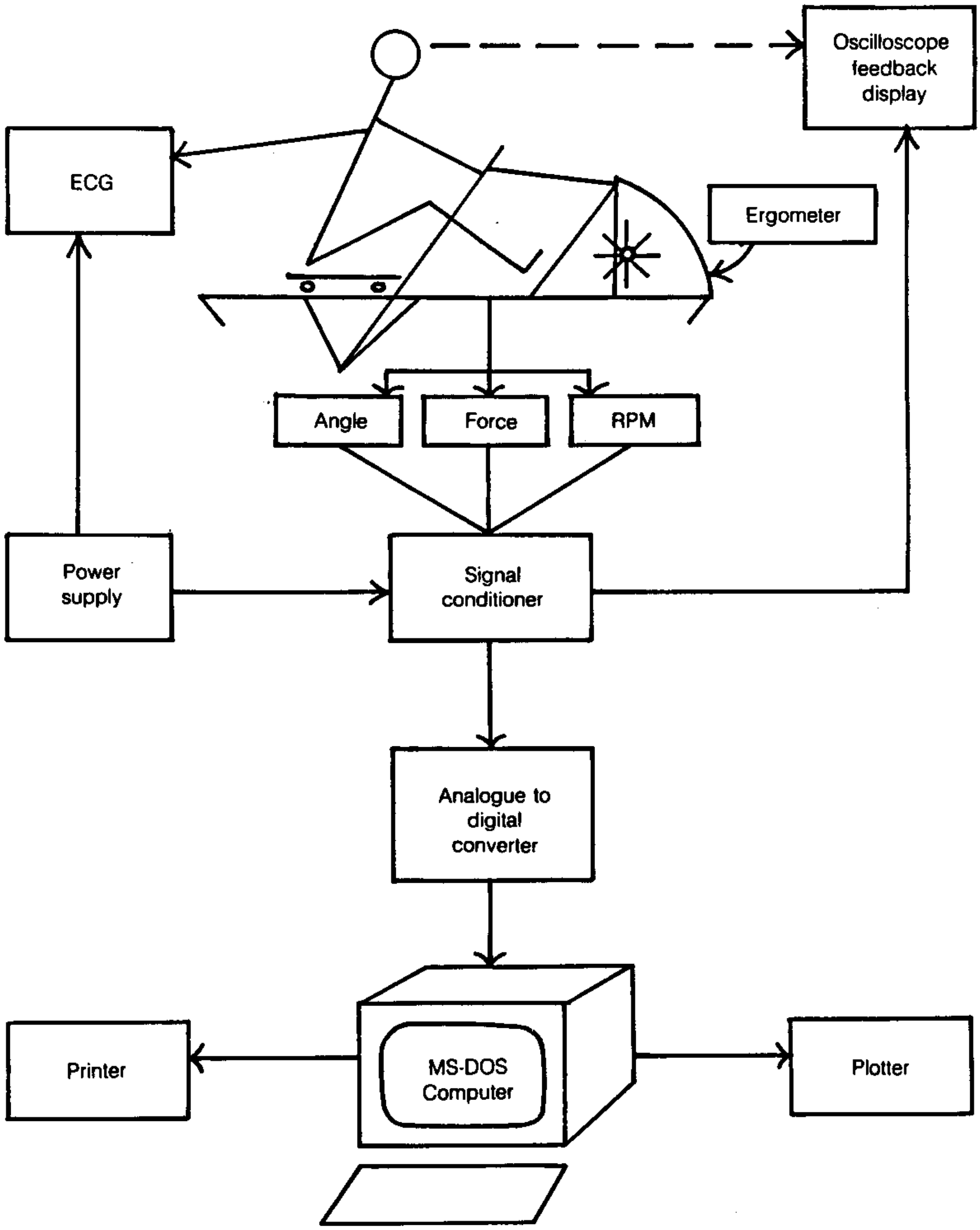


**Figure 28** Structure of the instrumentation system

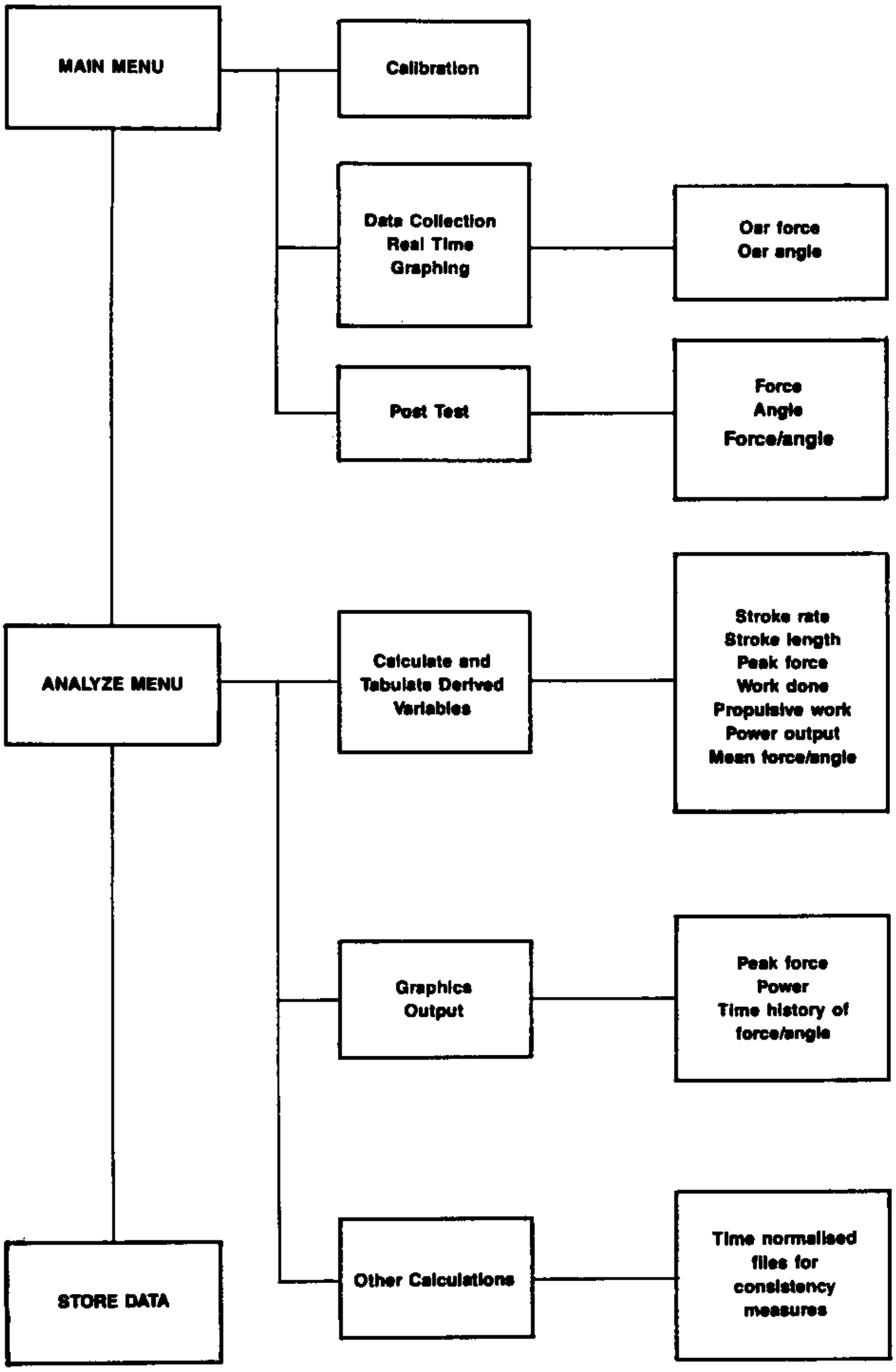


Figure 29 Software system for data analysis

For each test session, the subjects reported to the laboratory in comfortable rowing apparel and were then weighed to the nearest 50 grams on a calibrated balance scale. Height was then determined to the nearest millimetre on a Harpenden wall stadiometer. Laboratory temperature and humidity were controlled by an internal air conditioning system. The temperature of the testing area was maintained within the range 20 - 24.5 degrees celsius. The instructions given to all rowers are outlined in Appendix C.

A maximal rowing ergometer test provided the work situation for the measurement of work output variables. This test comprised a 4 minute warm-up period, followed by a 6 minute maximal effort wherein the subjects were required to adopt a stroke rate no lower than 31 strokes per minute. Prior to the test the subjects were urged to row at maximum pace. During the test, the subjects were informed of elapsed time every 30 seconds and of stroke rate every 20 seconds. For this purpose, stroke rate was determined by a hand-held stroke rate meter (Seiko, S101-5010).

Heart rate and electrocardiogram parameters were measured continuously during warm-up and maximal exercise conditions. Bipolar chest leads were attached to each subject's chest prior to testing. A CM5 lead configuration was utilized in which the leads were attached to electrodes (Nikomed Introde) sited on the manubrium and the V5 position.

All subjects were fully debriefed at the completion of the test, receiving a verbal briefing from the current author and a printout of the test results (see Appendix D).

The statistical procedure used in this phase of the study was multiple discriminant function analysis. This technique was chosen to determine the relative ability of the four variables, (a) mean propulsive power output per kilogram of body weight, (b) propulsive work consistency, (c) stroke-to-stroke consistency, and (d) stroke smoothness to predict individual rowing performance levels. As the analysis involved consideration of a nominal level dependent variable (level of rowing ability) with three constituent categories (novice, state, and national level rowers), multiple discriminant function analysis was used in preference to multiple correlation which is used to consider continuous dependent variables, and two-group discriminant function analysis which is used to predict to a dichotomous dependent variable (Huck, Cormier and Bounds, 1974).

### Phase two

All measures necessary for this phase of the study were collected during two testing sessions conducted within 7 days of each other. Both tests were conducted between the hours of 5 p.m. and 9 p.m. The first test served as a pretest with the subjects following the test protocol established in Phase One of the study. No feedback was provided at the completion of the pretest, the subjects were informed that the pretest results would be available immediately following the posttest. The phase two pretest instructions are outlined in Appendix E.

The subjects were randomly assigned to either the control or experimental group. Prior to the posttest warm-up, the subjects in the control group were informed of their total work output for the pretest and were shown a graphical representation of the force-angle profile which best reflected their average work output for the 6 minute pretest maximal effort.

The particular features of the force-angle profile and its relationship to total work output were explained (refer back to Figure 16, p. 99) and the control group subjects were then advised as to the strategies necessary to maximize work output via optimization of the force-angle profile. The posttest instructions given to the control group subjects are outlined in Appendix F. The control group subjects then undertook the warm-up and maximal work phases as per the pretest.

The subjects in the experimental group received the same set of instructions as the control group except that a template of the force-angle profile which represented the average work output for the pretest was placed on a dual persistence oscilloscope screen (Iiwatsu Synchroscope, SS-5416A) immediately in front of the rower in the normal plane of vision. On taking a stroke, the subject could immediately gauge the extent to which that stroke met the task criterion (augmented concurrent visual kinetic information feedback). The force-angle profile template was determined using the following procedure:

(1) The total work score for 6 minutes was divided by 12 in order to derive the average 30 second work output.

(2) The work output data for each 30 seconds of work was examined to find the nearest value to the average 30 second work output.

(3) A printout of the average force-angle profile for this work value was then obtained.

(4) The peak force for this force-angle profile was then determined.

(5) The peak force was multiplied by the factor derived from the division of the average work output for 30 seconds by the actual work output for the sample chosen, to bring it to the correct magnitude for the template.

(6) The printout of the average force-angle profile was then reduced to 6 centimetres to match the peak force and a transparency of this reduction was placed on the screen of the oscilloscope to act as the template.

A mass of 462.56 newtons was used to calibrate the vertical deflection of the oscilloscope so that the peak force as calculated in (5) above would produce a 6 centimetre vertical deflection of the oscilloscope. Fixed points corresponding to 0 degrees, plus 30 degrees and minus 30 degrees were used to calibrate horizontal deflection of the oscilloscope (see Figure 30). The oscilloscope display was set for long persistence and was available uninterrupted for the duration of the warm-up and maximal work phases. The experimental subjects were encouraged to use the oscilloscope display to maintain the response output force-angle profile curve just outside the template curve.

The specific instructions given to the experimental subjects are presented in Appendix G. On completion of the posttest, all subjects received immediate posttest feedback on the results of the test and were fully debriefed on the purposes of the study (see Appendix H).

This study involved random assignment of subjects to two different treatment groups and collection of pretest and posttest data from each subject. The research design was representative of the pretest-posttest control group design (Huck et al. 1974) and is outlined in Figure 31.

This phase of the study involved a single independent variable, the provision of augmented concurrent information feedback and two dependent variables, namely, propulsive work consistency and mean propulsive power output per kilogram of body weight. Statistical analysis of the data involved a single factor multiple analysis of covariance (MANCOVA) with pretest propulsive work consistency and mean propulsive power output per kilogram of body weight data acting as the covariates. The MANCOVA was used to compare the two groups in terms of

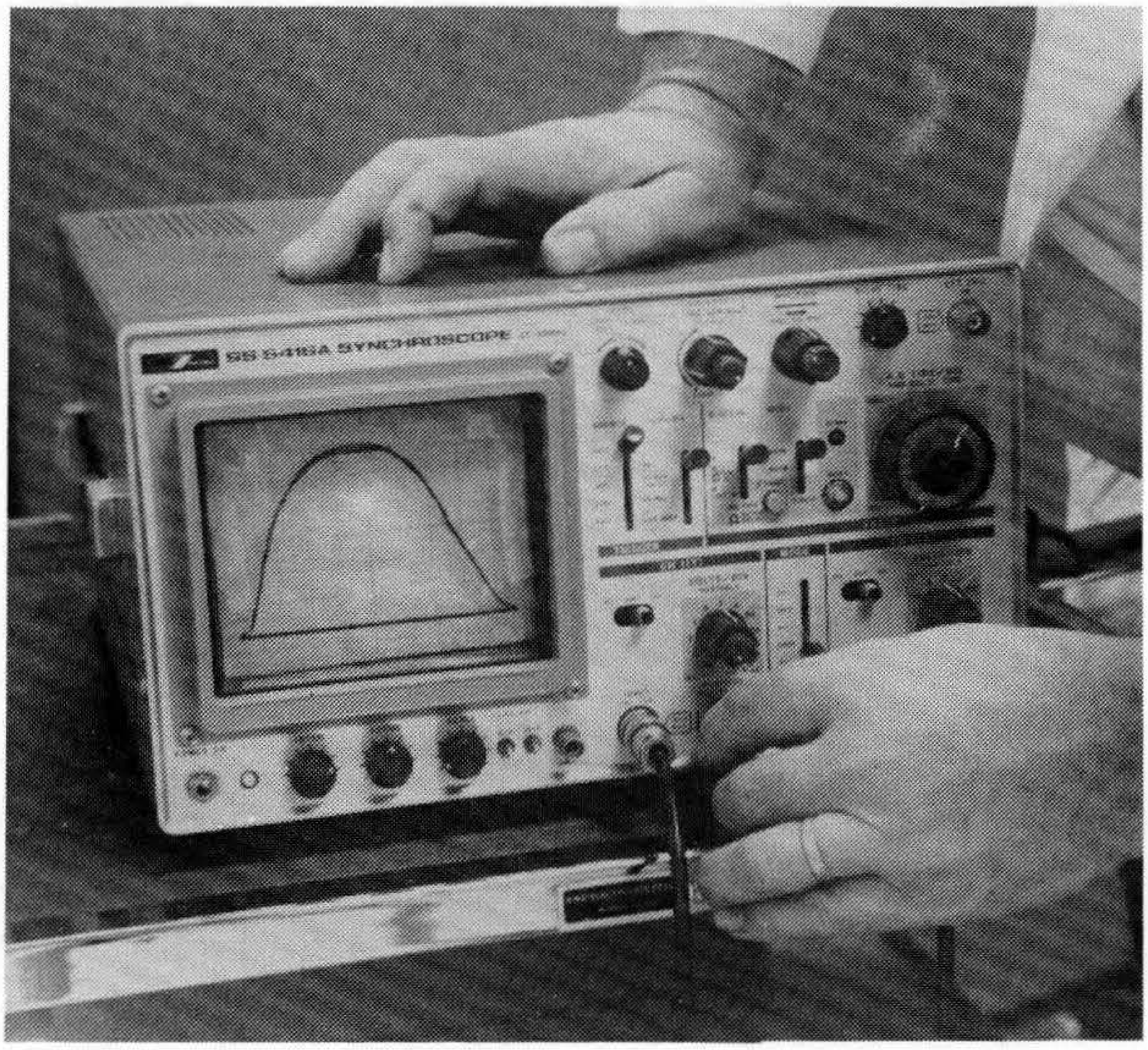


Figure 30 Calibration of vertical and horizontal oscilloscope deflection

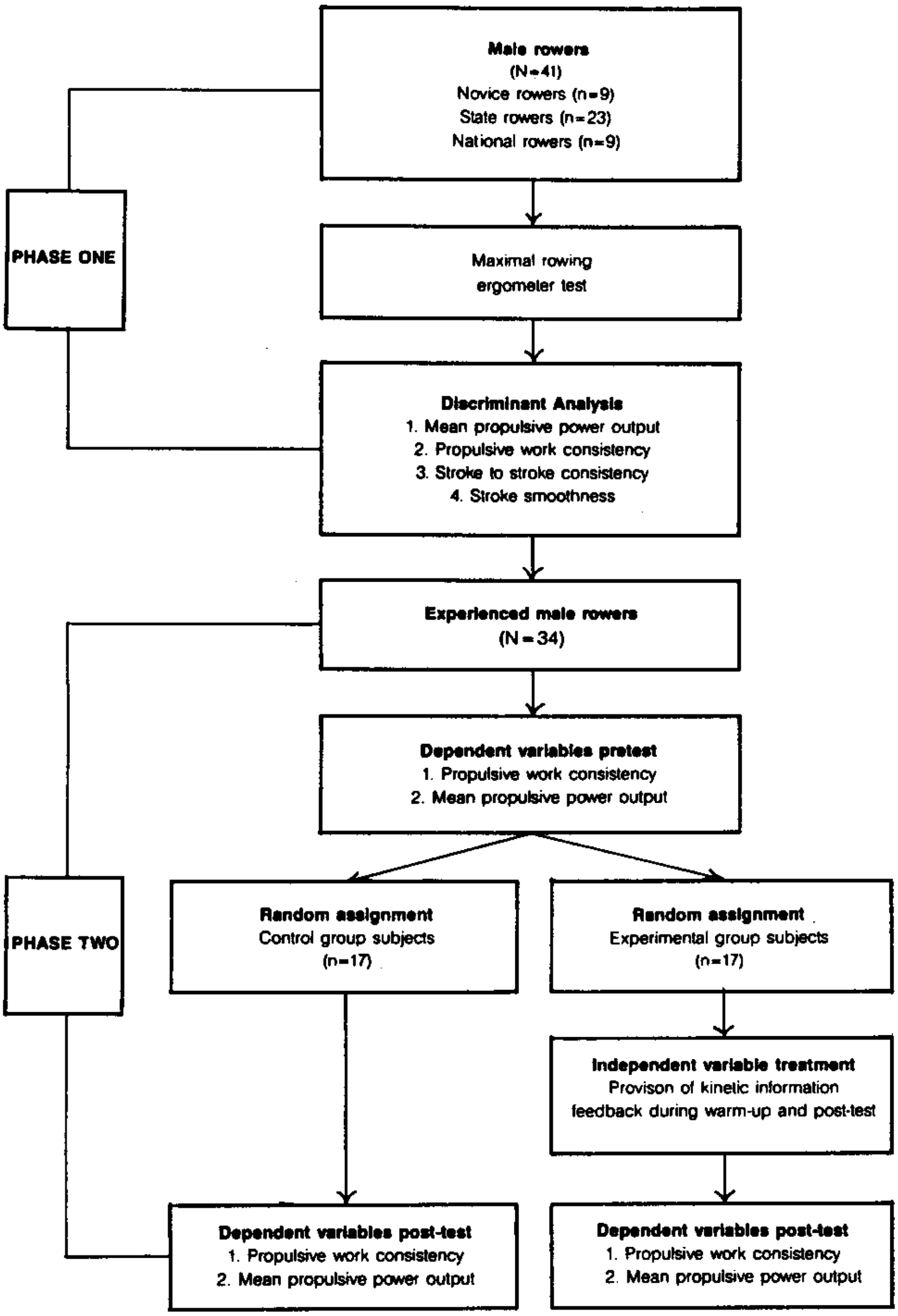


Figure 31 The research design

the posttest means, after these means had been adjusted to account for any differences that existed amongst the groups on the pretest.

As both treatment groups contained the same number of subjects, homogeneity of variance was assumed (Huck et al. 1974). However, it was necessary to test assumptions of common slope (homogeneity of regression) prior to accepting the MANCOVA analysis. A significance level of .05 was set for this study.

## Summary

### Phase one

Phase One of this study was conducted to determine the extent to which selected biomechanical performance variables discriminated between rowers of different ability levels. The variables chosen to describe rowing capacity and skill were mean propulsive power output per kilogram of body mass (watts/kg), propulsive work consistency (%), stroke-to-stroke consistency (%), and stroke smoothness (%). Mean propulsive power output per kilogram of body mass and propulsive work capacity were chosen to represent rowing capacity while stroke smoothness and stroke-to-stroke consistency served as technique measures. These variables were accessed through the oar handle force and oar angle information available from a Repco sweep oar rowing ergometer. Novice ($\underline{n}$=9), state ($\underline{n}$=23) and national level ($\underline{n}$=9) male rowers volunteered to participate in this phase of the study and undertook a maximal rowing ergometer test. The test comprised a 4 minute warm-up followed by a 6 minute maximal effort. The lower limit for work rate was set at 31 strokes per minute. The subjects were verbally encouraged to maintain work rate and peak force.

Oar force was determined via an XTRAN S1W 2KN S-beam load cell (Applied Measurement) attached in series with the rope of a wheeled Repco rowing ergometer. Calibration was achieved by hanging a known mass (462.5 newtons) from the load cell. Oar angle data was measured using a rotary potentiometer (Radio Spares, 173-580) with a 10 kilohm plastic element with a guaranteed linearity of 0.5%. Calibration was achieved by noting the oar angle at pre-determined points on the body of the ergometer in line with the travel path of the oar ($-30^{o}$, $0^{o}$, $+30^{o}$). Collected data was converted to digital form using a DT 2801 interface card (Data Translation) and was processed by an MS-DOS microcomputer.

Force and angle data were filtered with a cutoff frequency of 12.5 hertz and sampled over an 8 second period at 25 hertz every 30 seconds. The data collection rate was determined given a maximum frequency of 5 hertz for the rowing movements. Instantaneous force values were converted to torque values. Along with the variables of interest, collected data included stroke rate (per minute), stroke length (degrees), peak force (newtons), total work (joules), propulsive work (joules), and propulsive effectiveness (%).

Multiple discriminant function analysis was the statistical technique chosen to determine the ability of the four biomechanical performance variables to predict individual rowing performance levels.

### Phase two

The purpose of this phase of the study was to determine whether kinetic information feedback could be utilized to improve propulsive work consistency during maximal rowing and whether such improvement would result in an increase in mean propulsive power output per kilogram of body mass. Concurrent visual feedback of individual force-angle profile characteristics was used to modify the pattern of work output.

Club level male rowers ($\underline{N}$=34) volunteered to participate in this phase of the study and undertook two 6 minute maximal rowing ergometer efforts. The rowing ergometer test protocol was the same as that used for Phase One of this study. Following the first ergometer test (or pretest) the subjects were randomly allocated to a control ($\underline{n}$=17) or experimental ($\underline{n}$=17) group. The second or posttest was conducted 7 days after the pretest. Prior to the posttest all subjects were advised of their pretest results and the strategies necessary to maximize work output via optimization of the force-angle profile.

The experimental group subjects received concurrent visual kinetic information feedback in the form of stroke-to-stroke force-angle profiles compared to a template of the force-angle profile which represented the average pretest work output. This template was placed on an oscilloscope screen in front of the rower. On taking a stroke, the rower could immediately gauge the extent to which that stroke met the task criterion. The concurrent kinetic information feedback was provided uninterrupted for the duration of the warm-up and the maximal effort. The instrumentation calibration procedures, data collection methods, and processed data files were the same as those utilized in Phase One of this study. Single factor multiple analysis of covariance was used to test for significant differences between both groups of subjects for posttest scores for propulsive work consistency and mean propulsive power output per kilogram of body mass.

# Chapter 4

# RESULTS AND DISCUSSION

## Overview

Phase one of this study was undertaken to study the differences between three groups of rowers with respect to selected biomechanical performance variables namely, mean propulsive power output per kilogram of body mass, propulsive work consistency, stroke-to-stroke consistency and stroke smoothness. Phase two of this study examined the effects of kinetic information feedback, provided during maximal ergometric rowing, on propulsive work consistency and mean propulsive power output per kilogram of body mass. Concurrent visual presentation of stroke-to-stroke force-angle profile characteristics compared to a criterion force-angle profile template served as kinetic information feedback.

## Phase one results and discussion

The results of each group of rowers for the four biomechanical performance variables are presented in Table 2. Individual subject data for each of the biomechanical performance variables is presented in Appendix J. A sample subject data file is shown in Appendix I.

The strength of the relationship between the corresponding pair of variables within the groups is indicated in Table 3. The within-groups

**Table 2**

**Mean Data for Mean Propulsive Power Output per kilogram of Body Mass (MPPO), Propulsive Work Consistency (PWC), Stroke-to-Stroke Consistency, and Stroke Smoothness (SMO)**

| Group | | Biomechanical Performance Variables | | | |
|---|---|---|---|---|---|
| | | MPPO (watts/kg) | PWC (%) | SSC (%) | SMO (%) |
| Novice Rowers | M | 2.97 | 87.7 | 84.6 | 69.8 |
| (n = 9) | SD | 0.41 | 5.8 | 6.2 | 6.0 |
| State Rowers | M | 3.69 | 88.7 | 92.3 | 72.6 |
| (n = 23) | SD | 0.47 | 5.0 | 1.6 | 3.6 |
| National Rowers | M | 4.61 | 90.2 | 93.3 | 73.3 |
| (n = 9) | SD | 0.19 | 2.4 | 0.9 | 2.8 |
| Total | M | 3.73 | 88.8 | 90.8 | 72.1 |
| (N = 41) | SD | 0.68 | 4.7 | 4.5 | 4.2 |

correlation procedure assumed that the subjects were drawn either from the same population or from group populations that had identical dispersion patterns and was a better estimate of the relationship between the variables than the total correlations. The total correlation procedure encompassed the total range of subject data and was influenced by the differences in the group centroids (Klecka, 1980).

**Table 3**
**Pooled Within-Groups Correlation Matrix**

| Variable | MPPO | PWC | SSC | SMO |
|---|---|---|---|---|
| MPPO | 1.00 | | | |
| PWC | 0.41 | 1.00 | | |
| SSC | 0.51 | 0.18 | 1.00 | |
| SMO | 0.07 | -0.30 | 0.23 | 1.00 |

The pooled within-groups correlation matrix (Table 3) indicated that there were no high correlations between any corresponding pair of variables, the highest being between propulsive work consistency and mean propulsive power output per kilogram of body mass (0.41), and stroke-to-stroke consistency and mean propulsive power output per kilogram of body mass (0.51). This finding indicated the relatively independent origin of the four biomechanical performance variables chosen to describe rowing capacity and skill. The statistical properties of the variables in a discriminant analysis are limited by high correlations or linear combinations of variables which lead to redundant information (Klecka, 1980).

Discriminant analysis indicated the presence of two discriminant functions. Function one defined the horizontal axis while the rules for deriving Function two required it to be perpendicular to Function one so that it represented information that was as independent as possible. Function two therefore, was the vertical axis. The discriminant coefficients were used to compute the position of subject data in the discriminant space.

Having established the presence of two discriminant functions the location of group centroids and individual subject data were placed on a two-function plot (see Figure 32). An analysis of Figure 32 indicated that the 3 groups of rowers were quite distinct. A group territorial map (see Figure 33) indicated that the group centroids were well separated with minimal overlap of individual subject data. Separate scatterplots of each group of rowers are presented in Figures 34 to 36.

Standardised canonical discriminant function coefficients were then used to ascertain which variables contributed most to determining scores on the function. The standardised canonical discriminant function coefficients are presented in Table 4.

For Function one, mean propulsive power output per kilogram of body mass made the greatest contribution. Propulsive work consistency, stroke-to-stroke consistency and stroke smoothness were next in rank order. Each of these three variables individually contributed approximately half as much as mean propulsive power output per kilogram of body mass. On Function two, stroke-to-stroke consistency made

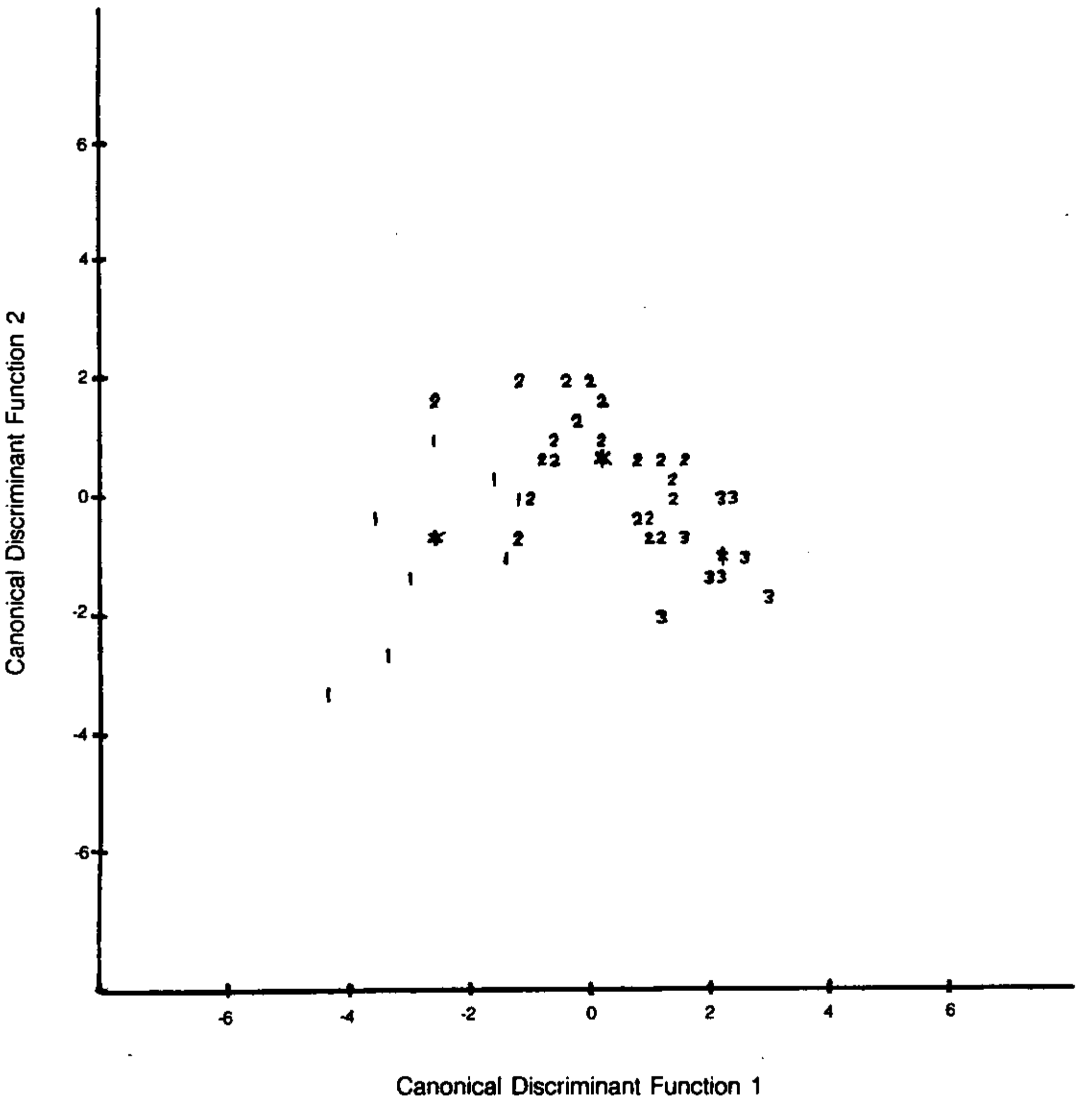


**Figure 32** Two function all-groups scatterplot
(* = group centroid)

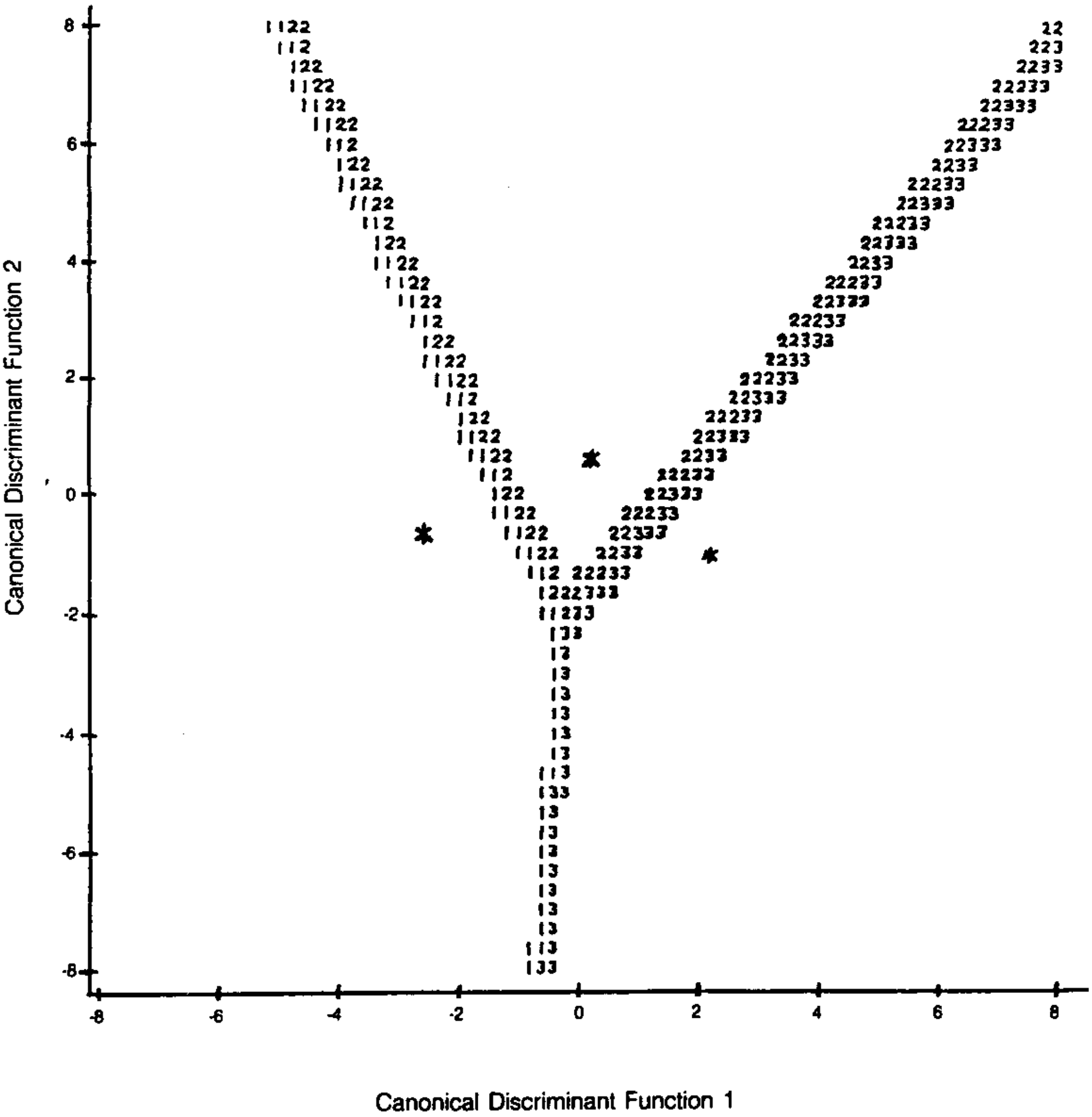


Figure 33 Group territorial map
(* = group centroid)

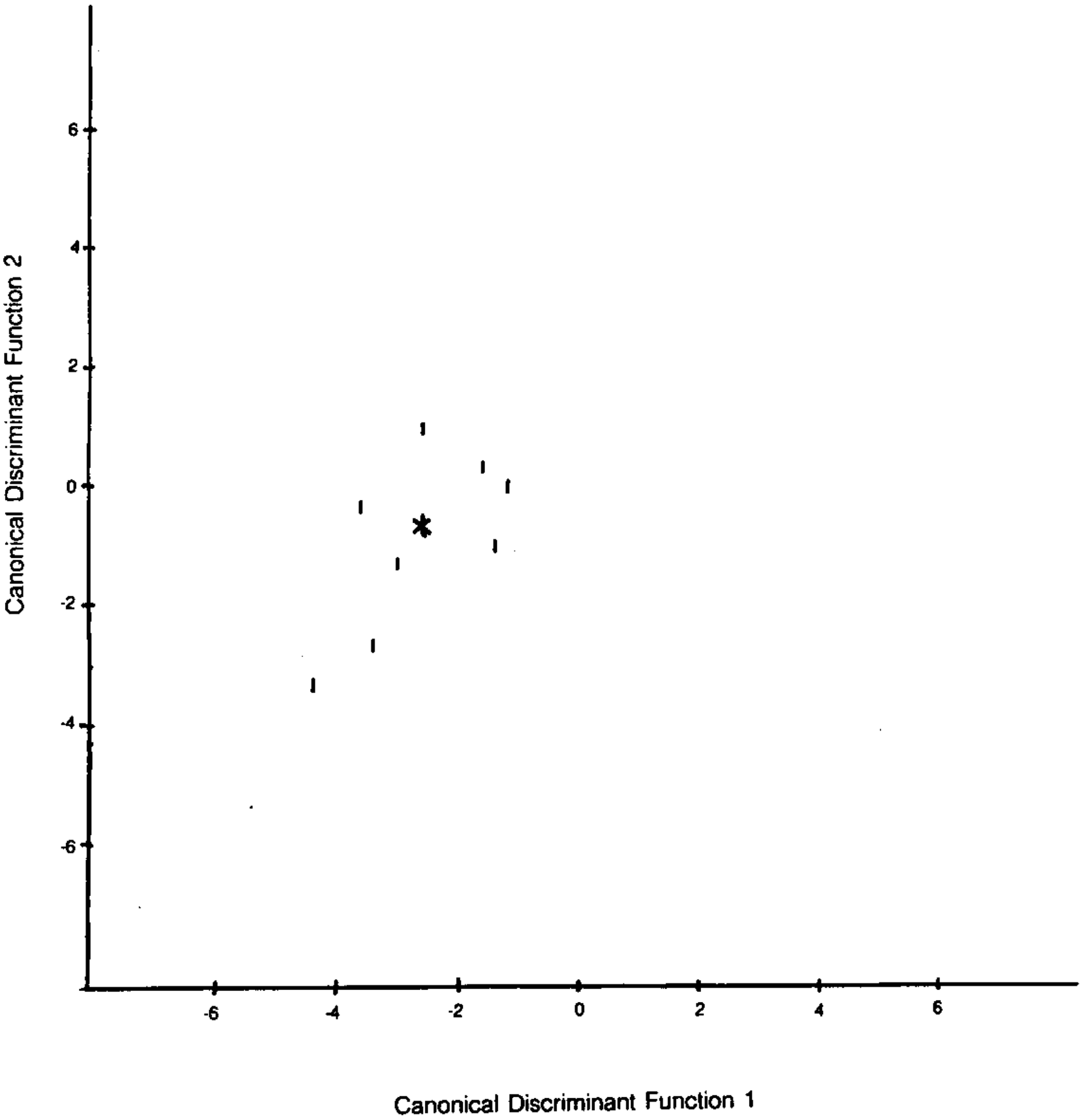


**Figure 34** Two function scatterplot for novice level rowers (* = group centroid)

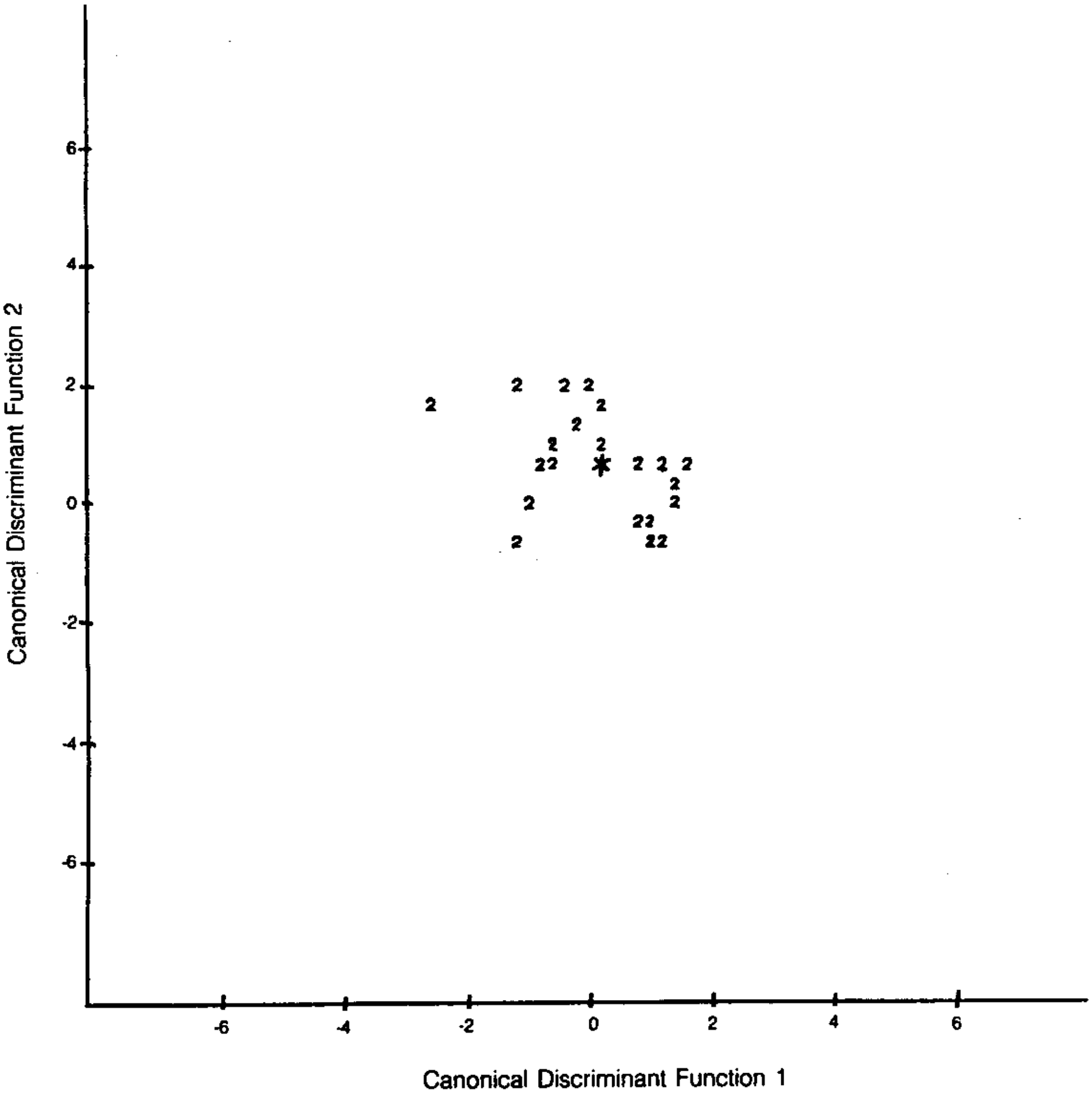


**Figure 35** Two function scatterplot for state level rowers (* = group centroid)

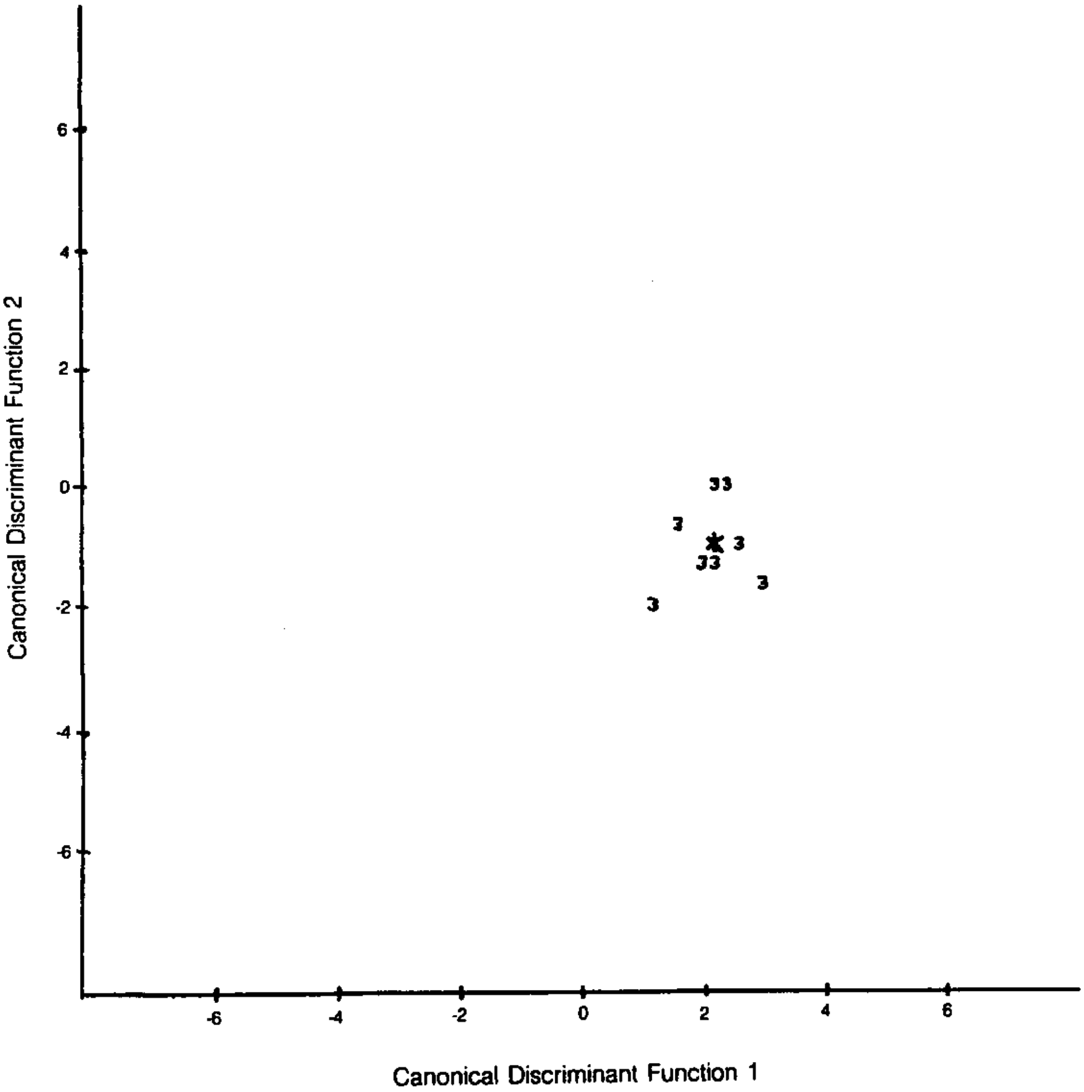


**Figure 36** Two function scatterplot for national level rowers (* = group centroid)

**Table 4**
**Standardised Canonical Discriminant Function Coefficients**

| Variable | Standardized Coefficient | |
|---|---|---|
| | Function 1 | Function 2 |
| MPPO | 0.83 | -0.94 |
| SSC | 0.49 | 1.05 |
| PWC | -0.50 | 0.10 |
| SMO | 0.40 | 0.48 |

the greatest contribution closely followed by mean propulsive power output per kilogram of body mass lesser contributions were evident from stroke smoothness and propulsive work consistency in particular.

Both discriminant functions clearly indicated the importance of mean propulsive power output per kilogram of body mass as a discriminating variable. Function two gave greater weight to the skill based variables stroke-to-stroke consistency and stroke smoothness than did Function one.

Function one had the largest eigenvalue and therefore, was the most powerful discriminator. The eigenvalues were converted into relative percentages by summing all of the eigenvalues to derive a measure of the total discriminating power with the result then being divided into each individual eigenvalue (Klecka, 1980). The relative percentage for Function two was considerably lower than that for Function one. Therefore, Function two was least informative regarding the differences between the groups of rowers.

Canonical correlation coefficients were determined in order to summarize the degree of relatedness between the groups and the discriminant function. A high coefficient was found for Function one indicating a strong relationship between the groups of rowers and the first discriminant function. The second function had a lower coefficient indicating a weaker association, as reflected in the relative percentage. Thus Function one had greater utility in explaining group differences. However, the size of the canonical correlation coefficients served to indicate that the groups of rowers were different with regard to the variables being analyzed. Derived eigenvalues, relative percentages and canonical correlation coefficients are shown in Table 5.

The statistical significance of the discriminant functions was examined by determining the ability of the biomechanical performance variables to discriminate among the groups of rowers beyond that information previously computed. This "residual discrimination" utilized Wilks' Lambda ( $\Lambda$ ) as a multivariate measure of group differences over the discriminating variables. Results for tests of the statistical significance of the discriminant functions are outlined in Table 6.

**Table 5**
**Eigenvalues, Relative Percentages and Canonical Correlation Coefficients**

| Canonical Discriminant Function | Eigenvalue | Relative Percentage | Canonical Correlation |
|---|---|---|---|
| 1 | 2.75577 | 82.46 | 0.857 |
| 2 | 0.58604 | 17.54 | 0.608 |

**Table 6**
**Residual Discrimination and Tests of Significance**

| Functions Derived, k | Wilks' Lambda | Chi-Square | Degrees of Freedom | Significance Level |
|---|---|---|---|---|
| 0 | 0.1679 | 65.135 | 8 | 0.0000 |
| 1 | 0.6305 | 16.835 | 3 | 0.0008 |

Wilks' Lambda for the biomechanical performance data was computed prior to the derivation of discriminant functions ($\underline{k}$=0) and resulted in a value for Wilks' Lambda which was close to 0 ($\Lambda$=0.1679). This value indicated that the group centroids were well separated and distinct relative to the amount of dispersion within the groups. The derivation of the first discriminant function removed a considerable amount of the discriminant information from the equation. The size of the second Wilks' Lambda ($\underline{k}$=1, $\Lambda$=0.6305) indicated that the residual discrimination was of doubtful value, given that Wilks' Lambda values which approach 1.0 report progressively less discrimination. Similar indications were apparent following inspection of the relative percentages and canonical correlation coefficients. The derived Wilks' Lambda values served as a measure of association and were of less import than the relative percentages and canonical correlation coefficients due to the dependence of Wilks' Lambda on residual discrimination (Klecka, 1980).

Therefore, the significance of Wilks' Lambda was determined by converting it into an approximation of chi-square. The differences between the groups of rowers were highly significant for both discriminant functions ($\underline{k}$=0, $\underline{p}$=0.0000; $\underline{k}$=1, $\underline{p}$=0.0008). These results indicated that while the first function could represent much of the observed differences between the groups, the residual discrimination might add certain differences present in the population. Therefore, the derived discriminant functions were statistically significant as a set.

Following the interpretation of the canonical discriminant functions, classification procedures were used to predict the group to which a subject most likely belonged. This procedure involved defining the "distance" between each rower and each group centroid with the rower being classified into the "nearest" group.

Initially, classification function coefficients were derived by using the discriminating variables themselves to determine maximum group differences (Table 7). However, these coefficients were of limited value as no information was available regarding the statistical significance of the discrimination or of the dimensionality of the discriminant space. A more thorough analysis was conducted by basing the classification procedure on the canonical discriminant functions (Table 8).

**Table 7**
**Classification Function Coefficients**

| Variable | Group | | |
|---|---|---|---|
| | Novice | State | National |
| MPPO | -46.05 | -43.32 | -35.70 |
| SSC | 13.11 | 14.00 | 13.76 |
| PWC | 3.00 | 2.74 | 2.50 |
| SMO | 6.81 | 7.24 | 7.24 |
| CONSTANT | -845.14 | -951.23 | -939.01 |

**Table 8**
<u>Canonical Discriminant Functions Evaluated at Group Centroids</u>

| Group | Function 1 | Function 2 |
|---|---|---|
| Novice | -2.64075 | -.66951 |
| State | .19754 | .64559 |
| National | 2.13593 | -.98032 |

To obtain a clearer picture of how the subjects were classified, classification boundary lines from the territorial map (refer back to Figure 33, p.202) were superimposed over the scatterplot for all groups of rowers (refer back to Figure 32, p.201). The resulting territorial plot classification (see Figure 37) indicated the possible inclusion of one novice level rower in the state group, two state level rowers in the novice group and three state level rowers in the national group.

An additional measure of group differences was determined by deriving the percentage of "known" subjects that were correctly classified. The extent to which the rowers were correctly classified into their respective groups indicated the accuracy of the classification procedure and the degree of group separation. The classification procedure correctly placed 88.9% of the novice level rowers, 73.9% of the state level rowers and 100% of the national level rowers into their respective groups (see Table 9). One novice level rower was classified as a state level rower, 2 state level rowers were classified as novice

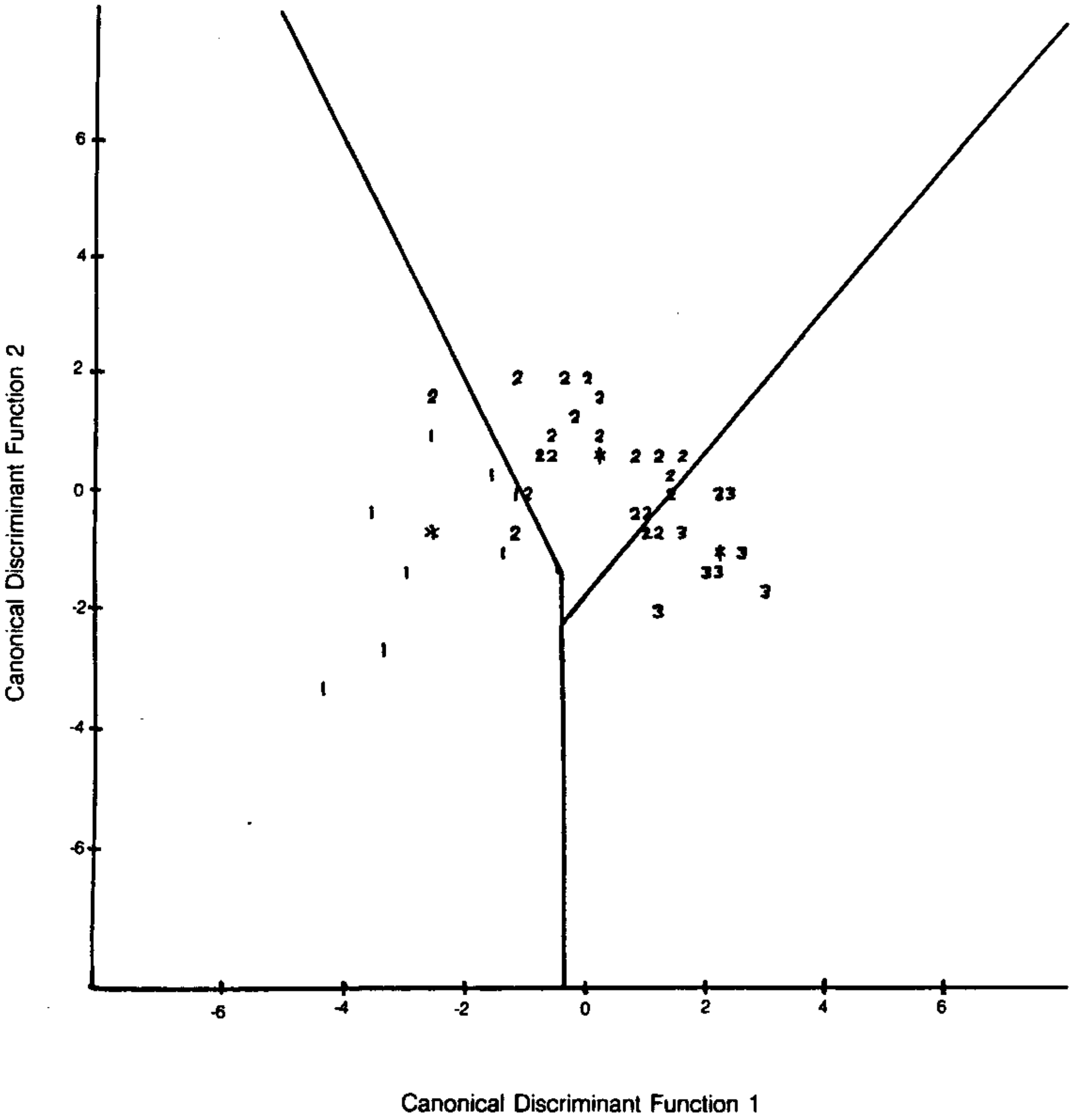


**Figure 37** **Subject classification by territorial plot (* = group centroid)**

level rowers and 4 were classified as national level rowers. None of the national level rowers were misclassified.

**Table 9**
Classification Matrix

| Original Group | Number of Subjects | Predicted Group<br>1 | <br>2 | <br>3 |
|---|---|---|---|---|
| Novice (1) | 9 | 8<br>(88.9%) | 1<br>(11.1%) | 0<br>(0%) |
| State (2) | 23 | 2<br>(8.7%) | 17<br>(73.9%) | 4<br>(17.4%) |
| National (3) | 9 | 0<br>(0%) | 0<br>(0%) | 9<br>(100%) |

Of all 41 rowers, 82.93% were correctly classified into their respective groups by the weighted discriminant scores. When compared with the Wilks' Lambda and the canonical correlations, the percentage of correct classifications proved to be the most intuitive measure of the amount of discrimination contained in the biomechanical performance variables. The predictive accuracy of the biomechanical performance variables as measured directly by the percentage of rowers correctly classified was 2.49 times (or 49.6%) greater than the expected value if the rowers had been randomly assigned to groups. With 3 groups, 33.33% of correct predictions are possible with pure random assignment

(Klecka, 1980). Discriminant scores and classification information for each rower ~~is~~ are presented in Table 10.

The extent to which all of the biomechanical performance variables were valuable and necessary was determined via stepwise discriminant analysis. A forward stepwise procedure was utilized whereby the individual variable which provided the greatest univariate discrimination was selected first and was then paired with each of the remaining variables one at a time, to determine the combination which produced the greatest discrimination.

Wilks' Lambda and an equivalent F statistic were used as measures of discrimination for the stepwise procedure. Wilks' Lambda took into account both the differences between the groups and the level of homogeneity within the groups. As Wilks' Lambda is an inverse statistic, the variable which produced the smallest Lambda was selected for that step. When Lambda was converted into an F statistic the largest F was chosen. A partial multivariate F statistic, known as the F-to-enter, was chosen in preference to the overall F. The F-to-enter allowed testing of the additional discrimination introduced by a biomechanical performance variable being considered after taking into account the discrimination achieved by the other variables already entered (Dixon, 1973). The F statistic was also used as a test of significance in order to determine if each step was statistically

**Table 10**
**Subject Discriminant Scores and Classification Information**

| | Actual | Highest | Probability | | 2nd highest | | Discriminant | |
|---|---|---|---|---|---|---|---|---|
| Subject | Group | Group | P(X/G) | P(G/X) | Group | P(G/X) | Scores | |
| 1 | 1 | 1 | .5567 | .9994 | 2 | .0006 | -3.6822 | -.3746 |
| 2 | 1 | 1 | .0091 | 1.0000 | 2 | .0000 | -4.3419 | -3.2188 |
| 3 | 1 | 1 | .6479 | .9993 | 2 | .0007 | -3.0843 | -1.4889 |
| 4 | 1 | 1 | .1947 | .8969 | 2 | .1031 | -2.5152 | 1.1352 |
| 5 | 1 | 1 | .3563 | .6750 | 2 | .3244 | -1.6627 | .3828 |
| 6 | 1 | 1 | .1275 | .9999 | 2 | .0001 | -3.4038 | -2.5503 |
| 7 | 1 | 1 | .3168 | .9299 | 2 | .0701 | -2.5285 | .8425 |
| 8 | 1 | 1 | .4633 | .8445 | 2 | .1522 | -1.4196 | -.8875 |
| 9 | 1*** | 2 | .3641 | .6094 | 1 | .3863 | -1.1286 | .1340 |
| 10 | 2 | 2 | .5428 | .6207 | 3 | .3767 | .8314 | -.2600 |
| 11 | 2*** | 3 | .4661 | .5295 | 2 | .4701 | 1.3366 | -.0381 |
| 12 | 2 | 2 | .8793 | .8986 | 3 | .0998 | .7047 | .6336 |
| 13 | 2 | 2 | .6415 | .9895 | 3 | .0081 | .1564 | 1.5869 |
| 14 | 2*** | 3 | .4536 | .5338 | 2 | .4646 | .9894 | -.4641 |
| 15 | 2 | 2 | .3507 | .9953 | 3 | .0032 | .0968 | 2.0897 |
| 16 | 2 | 2 | .7537 | .9808 | 1 | .0130 | -.2747 | 1.2307 |
| 17 | 2 | 2 | .7752 | .9327 | 1 | .0568 | -.5138 | .5887 |
| 18 | 2 | 2 | .4008 | .5154 | 3 | .4844 | 1.4940 | .2610 |
| 19 | 2*** | 3 | .5492 | .6486 | 2 | .3503 | 1.1004 | -.6253 |
| 20 | 2 | 2 | .8949 | .9785 | 3 | .0170 | .1498 | 1.1143 |
| 21 | 2 | 2 | .4016 | .9921 | 1 | .0059 | -.3011 | 1.9010 |
| 22 | 2*** | 3 | .4759 | .5921 | 2 | .4060 | .9662 | -.6385 |
| 23 | 2 | 2 | .5780 | .7779 | 3 | .2219 | 1.2435 | .6957 |
| 24 | 2 | 2 | .5563 | .8833 | 1 | .1132 | -.8743 | .8006 |
| 25 | 2 | 2 | .4291 | .5547 | 3 | .4451 | 1.4546 | .3112 |
| 26 | 2 | 2 | .3542 | .6494 | 3 | .3505 | 1.6330 | .7678 |
| 27 | 2 | 2 | .7225 | .9585 | 1 | .0361 | -.5308 | .9915 |
| 28 | 2 | 2 | .4161 | .6757 | 1 | .3183 | -1.0220 | .1294 |
| 29 | 2*** | 1 | .3651 | .6830 | 2 | .3108 | -1.2226 | -.6084 |
| 30 | 2 | 2 | .7996 | .8828 | 3 | .1163 | .8625 | .7167 |
| 31 | 2 | 2 | .1460 | .9377 | 1 | .0621 | -1.2051 | 2.0170 |
| 32 | 2*** | 1 | .0679 | .8229 | 2 | .1771 | -2.5315 | 1.6471 |
| 33 | 3 | 3 | .9571 | .9758 | 2 | .0242 | 2.1434 | -1.2764 |
| 34 | 3 | 3 | .7902 | .8125 | 2 | .1874 | 1.6352 | -.5111 |
| 35 | 3 | 3 | .5807 | .9971 | 2 | .0029 | 2.9167 | -1.6713 |
| 36 | 3 | 3 | .6106 | .8493 | 2 | .1507 | 2.2079 | .0104 |
| 37 | 3 | 3 | .9961 | .9655 | 2 | .0345 | 2.1301 | -1.0681 |
| 38 | 3 | 3 | .9003 | .9835 | 2 | .0165 | 2.5941 | -.9809 |
| 39 | 3 | 3 | .4061 | .9520 | 2 | .0474 | 1.2142 | -1.9563 |
| 40 | 3 | 3 | .9151 | .9698 | 2 | .0302 | 1.9552 | -1.3608 |
| 41 | 3 | 3 | .5977 | .8988 | 2 | .1012 | 2.4267 | -.0084 |

*** = misclassified subjects; P(X/G) = probability of a subject in group G being that far from the centroid; P(G/X) = probability of the subject being in group G and having a score X significant. The stepwise discriminant analysis using Wilks' Lambda as the inclusion criterion included the biomechanical performance variables in the order, mean propulsive power output per kilogram of body mass, stroke-to-stroke consistency, stroke smoothness and propulsive work consistency. All increments were statistically significant ($p<.001$). A summary table for the stepwise discriminant analysis is presented in Table 11.

**Table 11**
**Summary Table for the Stepwise Discriminant Analysis**

| Step | Action<br>Entered | <br>Removed | Variables In | Wilks' Lambda | Significance Level |
|---|---|---|---|---|---|
| 1 | MPPO | | 1 | .344520 | .0000 |
| 2 | SSC | | 2 | .223872 | .0000 |
| 3 | SMO | | 3 | .192751 | .0000 |
| 4 | PWC | | 4 | .167875 | .0000 |

The mean data (refer back to Table 2, p.198) for the three groups of rowers indicated that there is a positive relationship between performance level and each of the biomechanical performance variables. It was also apparent that the variability within a group of rowers decreased as the performance level increased. This finding would tend to support the contention that rowing is a motor skill that requires high levels of consistency, coherence, accuracy and continuity particularly at the elite level. The relatively fixed rowing environment calls for the development of a highly consistent movement pattern once that pattern has been established as being efficient. The ability to stay in time with other crew members and to obtain maximum propulsion is largely dependent upon the accurate and continuous replication of efficient stroke patterns.

The four biomechanical performance variables that were chosen to describe rowing capacity and skill were shown to be adequately independent of each other (refer back to Table 3, p.199). All four variables made a significant contribution to discrimination between the groups of rowers although propulsive work consistency was the least effective discriminator and was therefore, added last in the stepwise discriminant analysis. Comparisons between novice and national level rowers for propulsive work consistency, stroke-to-stroke consistency and stroke smoothness are shown in Figures 38, 39 and 40. Figure 38 represents propulsive work consistency scores of 81% for a novice level rower and 97% for a national level rower. Figure 39 indicates a stroke-to-stroke consistency score of 73% for a novice level rower and 94% for a national level rower. Indicated IN THIS FIGURE are five consecutive strokes for one of the thirty second samples of force-angle data. Figure 40 represents smoothness scores of 61% for a novice level rower and 76% for a national level rower. It is apparent that the second harmonic is present in greater proportion in the novice level rower than in the national level rower.

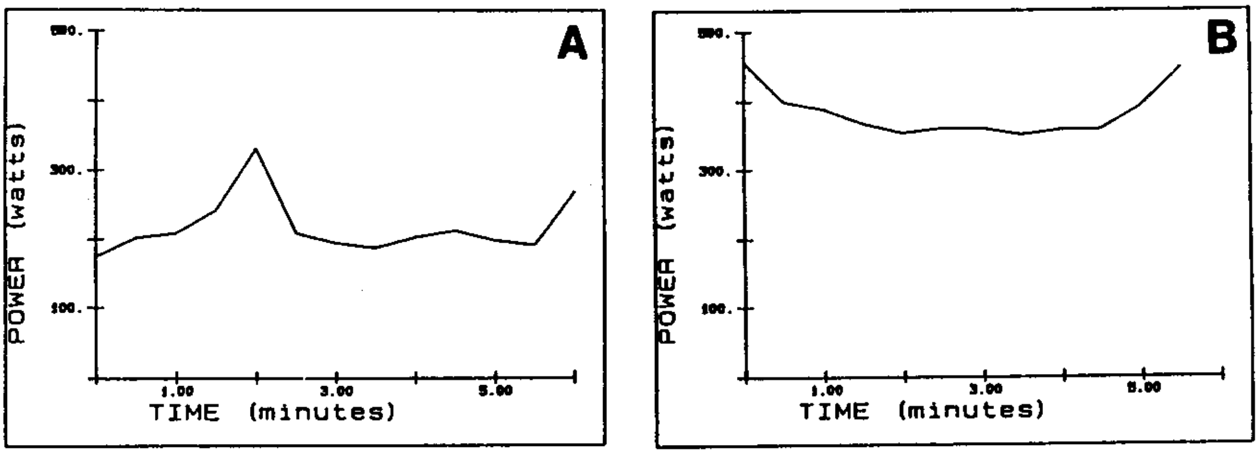


**Figure 38** Total power output of a novice (A) and national (B) level rower for a 6 minute maximal rowing ergometer test

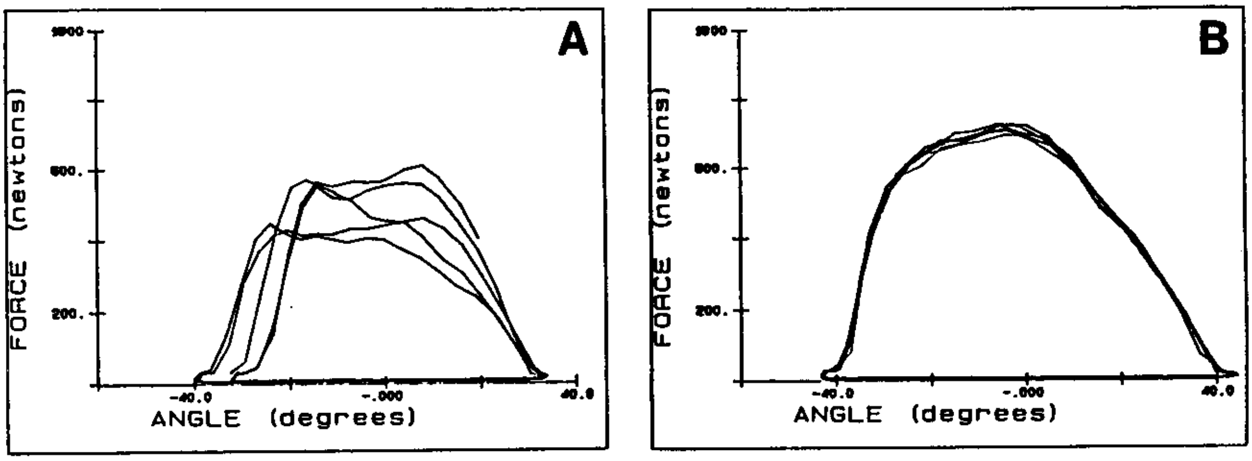


**Figure 39** **Oar force and oar angle data for five consecutive strokes for a novice (A) and a national (B) level rower**

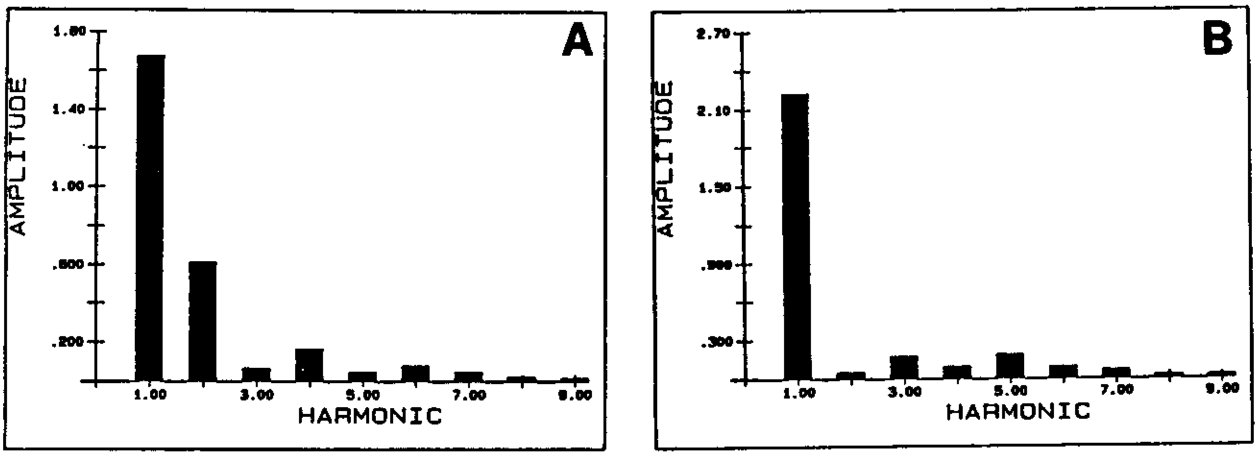


**Figure 40** **Fourier transforms of averaged force data of a novice (A) and a national (B) level rower**

Both discriminant functions (refer back to Table 4, p.206) gave a relatively heavy weighting to mean propulsive power output per kilogram of body mass thus confirming the importance of this variable as a discriminant variable. The first discriminant function also gave some significant weighting to each of the other three variables. The second discriminant function gave greater weighting to the skill-based variables stroke-to-stroke consistency and stroke smoothness than the first discriminant function. If it was deemed necessary to create two separate dimensions concerning maximal rowing performance, one related to power and one related to skill, then a rotation of the axes of the discriminant functions could be carried out to facilitate this.

The classification coefficients shown in Table 7 (refer back to p.210) could be used in an equation to determine the likelihood of an individual male rower's membership of any one of the three groups of rowers. The group of rowers which has the highest score of any individual male rower will determine the most likely group membership.

Given that the aim of competitive rowing is to cover the race distance in the shortest possible time, it is not surprising that mean propulsive power output per kilogram of body mass was the most important discriminator between the groups of rowers. However, as hypothesized, propulsive work consistency, the second measure of work capacity utilized in this study, proved to be the least effective discriminator. This would suggest that male rowers of all ability levels make greater relative use of skill based biomechanical performance variables such as stroke-to-stroke consistency and stroke smoothness in order to maximize propulsive effort than adoption of the most effective pattern of power output. In other words, there is a trade-off between skill and pace considerations.

The results of phase one of this study confirmed that the pattern of energy production utilized by rowers is common across all ability levels and represents a "U" shaped pattern of power output which, in turn, indicates a lack of consistency in work output. There is support (Hagerman, 1984) for the contention that this pattern of energy production is rather inefficient with the rower incurring the majority of a large oxygen deficit during the first 30 to 90 seconds of a race, and then being required to draw upon a considerable aerobic capacity to meet energy demands during the next 4 minutes. Anaerobiosis takes on greater importance during the last 30 to 60 seconds of a race when crews traditionally undertake a finishing sprint.

Concern with the physiological principles of rowing performance led Klavora (1979a; 1982b) to propose the utilization of an even pace or "best performance" strategy when attempting to lower set times in qualifying trials for national crew selection or when opposing far superior crews. The even pace strategy proposed by Klavora requires a crew to begin a race at the highest possible pace that can be maintained for the race distance with maximum oxygen debt occurring in the last stroke of the race. A crew utilizing this pacing regime would commence the race with a "moderately" fast start and then undertake an invariant work output pattern for the duration of the race. No mid race sprints would be attempted nor would there be a finishing sprint. Rowing in this manner should result in largely identical split times for each 500 metres (Klovara, 1982b).

The successful use of the even pace strategy in World Championship rowing events was seen by Klavora as being very convincing. For example, in winning the 1977 World Championship in the coxless four, the New Zealand crew produced only a 2 second difference between the slowest and fastest 500 metre pieces while the difference between the first and second 1000 metres was only 22/100 of a second. Other convincing examples of the even pace strategy included the 1974 and 1975 World Championship performances of the 1977 World Champions in the double sculls from Great Britain. In 1975 this pair produced only 1.41 seconds difference between the fastest and slowest 500 metre pieces while the first 1000 metres was only 77/100 of a second slower than the second 1000 metres. Pertti Karppinen's gold medal winning performance in the single scull in the Montreal Olympics was also seen as a good example of the value of an even pace strategy (Klavora, 1982b).

Pace is an important, but controversial, topic. However, even pace strategy has received support in the literature (Adams, 1968; Ariyoshi et al. 1979; Morehouse and Miller, 1976). Figure 41 indicates the

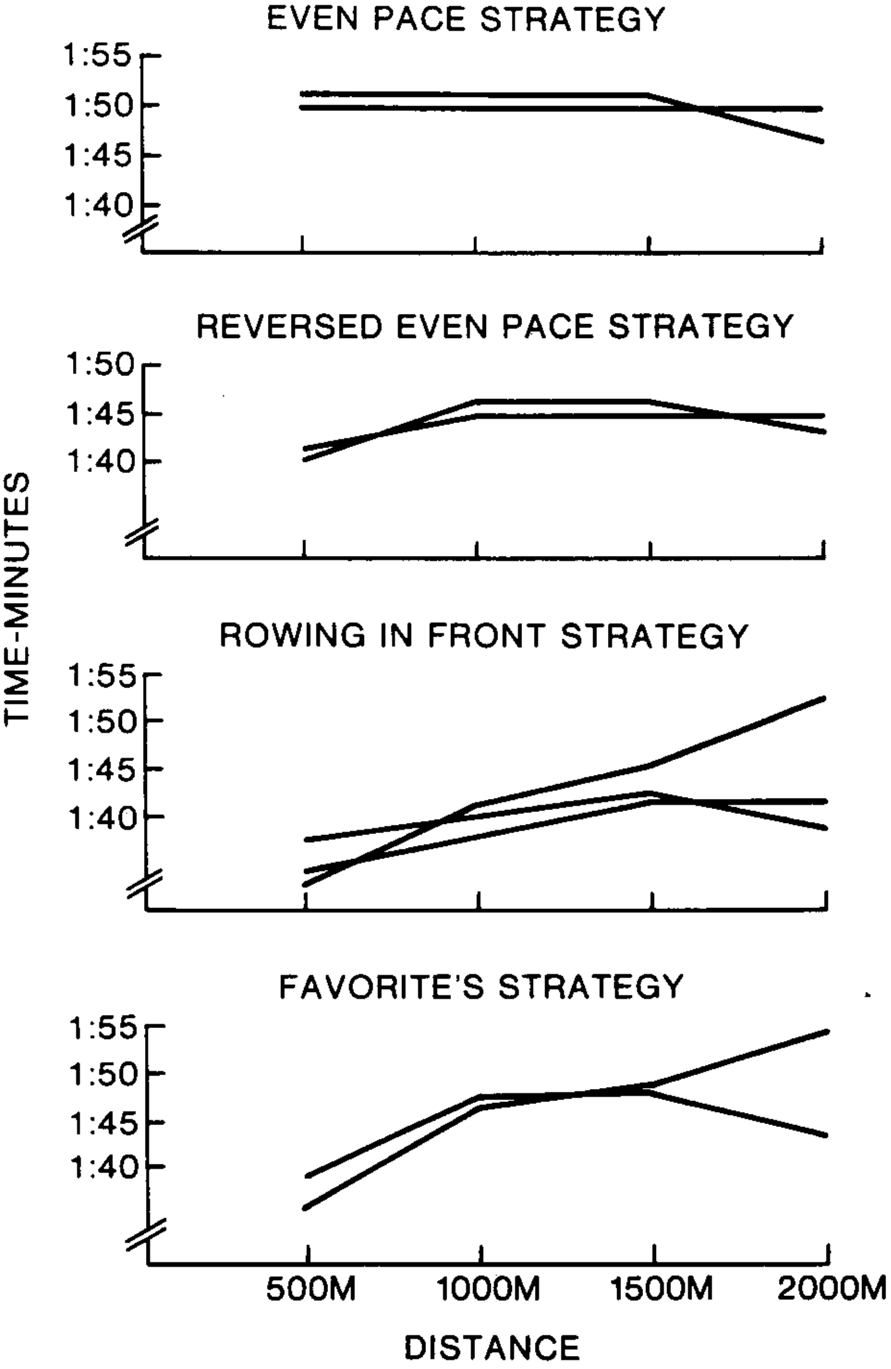


**Figure 41** Racing strategies utilized in international rowing competition (Klavora, 1982b)

predominant rowing strategies utilized in international rowing competition.

Ariyoshi et al. (1979) found that a fast early pace was preferable to a conservative start when establishing an even pace running strategy. These researchers examined the physiological reasons for the success of this pattern of pacing by considering (a) time to exhaustion, (b) total oxygen requirements and (c) heart rate. It was suggested that the effects of fatigue may lead to increased physiological effort as the race progresses. The main concern (Daniels, 1985) is whether or not a "metabolic drift" occurs with maximal constant velocity work over a 4 to 6 minute period.

It is clear from the above that the adoption of an even pace strategy during maximal rowing is related to the maximization of the relevant energy sources necessary for success in competitive rowing. Elite rowers are capable of sustaining a very high percentage of their absolute maximal oxygen uptake during a 6 minute maximal rowing effort. The importance of the aerobic component in the provision of energy during maximal rowing has been well documented (Hagerman, 1984; Morton et al. 1984; Secher, 1983; Spinks, 1988; Spinks, Moncrieff and Knight, 1984). However, there has been less consideration of the role of the anaerobic pathways in energy provision for maximal rowing.

It has been suggested (Hahn, 1985) that the participation of muscle phosphagen (adenosine triphosphate and creatine phosphate) catabolism in total energy release during rowing may be greater than previously thought, particularly as the recovery period of the rowing stroke probably allows some restoration of phosphagen stores. Hahn stated that a well developed phosphagen pathway and the ability to generate large energy releases from anaerobic glycolysis may be of considerable importance to maximal rowing performance.

Over-reliance on the development of the aerobic component may lead to a reduction in the amount of energy provided by anaerobic glycolysis (Costill, Fink and Pollock, 1976; Hahn, 1985; Telford, 1985). Prolonged high-volume aerobic training has been shown to result in an increase in the use of fatty acids to fuel trained muscle fibres (Mole, Oscai and Holloszy, 1971) and there is evidence (Armstrong, 1979) that fatty acid metabolism acts to inhibit anaerobic glycolysis. The "glucose-fatty acid cycle" was first described by Randle, Garland, Hales and Newsholme (1963) in cardiac muscle. They found that glucose uptake, glycolysis, glycogenolysis and pyruvate oxidation are partially inhibited in the myocardium by oxidation of fatty acids. An important factor in this inhibition was the accumulation of citrate which inhibited phosphofructokinase activity resulting in glucose-6-phosphate accumulation and inhibition of hexokinase. These findings were confirmed in rat skeletal muscle by Rennie and Holloszy (1977) who found that glucose uptake and lactate production was inhibited by approximately 30%. There is also the possibility that some of the fast twitch (IIa) muscle fibres will adapt to this type of training and contribute to aerobic rather than anaerobic metabolism (Telford, 1985). However, the extent to which the type IIa fibres are involved will depend upon the degree of activation of these fibres at relatively low levels of force production.

The concern expressed by Hagerman (1984) and Klavora (1979a; 1982b) regarding the "inefficient" or "uneconomical" pattern of energy production utilized by rowers appears to be based on the classic concept (Hill and Lupton, 1923) of lactate metabolism during heavy exercise. This theory suggested that a disproportionate relationship between oxygen supply and demand during exercise resulted in an "oxygen deficit" and muscle anaerobiosis which in turn, activated muscle glycogenolysis and glycolysis and lactic acid production. During recovery the "oxygen debt" was paid back and lactate was reconverted to glycogen. However, more recent research has indicated that the mechanisms of the "oxygen debt" and muscular fatigue are not readily explained by the lactic acid theory (Brooks, 1986; Brooks and Donovan, 1983; Brooks and Fahey, 1984; Donovan and Brooks, 1983; Eldridge, T'so and Chang, 1974; Issekutz, 1984).

Lactate is a dynamic metabolite in both resting and exercising individuals. Lactate production is highly correlated to metabolic rate during exercise, being the inevitable result of anaerobic glycolysis.

Lactate acts to maintain blood glucose through gluconeogenesis and to shuttle oxidizable substrate (lactate) from areas of high glycogenolytic rate to areas of high cellular respiration (Brooks, 1986). This latter process was seen by Brooks as an important form of substrate distribution, as a means of metabolic "waste" removal and as a means of co-ordinating anabolic and catabolic processes in various tissues for example, liver glyconeogenesis and glycogenesis and glycogenolysis, glycolysis and carbohydrate oxidation.

Lactate production and removal rates are equal during rest and light exercise as well as during heavier steady-state exercise when lactate levels remain elevated by a constant amount. The removal of lactate is concentration-dependant under these conditions. During non steady-state exercise lactate production and removal are related exponentially to oxygen uptake and linearly to the arterial lactate level. Thus, when blood lactate continues to increase during exercise, its production exceeds removal (Brooks, 1986; Brooks and Fahey, 1984). Blood lactic acid concentrations of around 3 to 5 millimoles per litre tend to indicate the onset of imbalance in lactate turnover. The point at which this imbalance occurs is referred to as the "anaerobic" or "lactate threshold" (Brooks and Fahey, 1984; Telford, 1985). The inability of lactate removal to keep pace with lactate production above the "lactate threshold" indicates that buffering capacity is inadequate to cope with the work load. For example, work loads of 120% of maximal oxygen uptake can be sustained at a constant power output for approximately 2 minutes but lactate removal is unable to cope with production (Medbo, Mohn, Tabata, Bahr, Vaage and Sejersted, 1988).

At a physiological pH, lactic acid dissociates hydrogen ions and it is the hydrogen ion concentration rather than lactate that causes blood and muscle pH to decrease. Lower pH levels inhibit phosphofructokinase and slow glycolysis and muscular function. Peak muscle force and work output are reduced and pain receptors are activated due to the presence of hydrogen ions in the blood supply to the brain (Brooks and Fahey, 1984; Parkhouse and McKenzie, 1984).

Creatine phosphate, inorganic phosphate, proteins (particularly carnosine), bicarbonate and increased intracellular fluid are recognized buffering agents in skeletal muscle (Costill, Verstappen, Kuipers, Janssen and Fink, 1984; Hermansen, Orheim and Sejersted, 1984; Hermansen and Vaage, 1977; Mainwood, Worsley-Brown and Paterson, 1972; Parkhouse and McKenzie, 1984; Wilkes, Gledhill and Smyth, 1983). These agents serve to limit rises in intracellular hydrogen ion concentration and Hahn (1985) has argued that the contribution of these agents should be well developed in rowers if considerable energy release from anaerobic glycolysis is to be achieved prior to the onset of fatigue.

Along with increased hydrogen ion concentration, muscular fatigue may be due to creatine phosphate decrement, changes in potassium and sodium ion distribution or altered calcium ion kinetics (Brooks and Fahey, 1984; Le Rumeur, Toulouse, De Certaines, Le Moyec and Le Bars, 1990). The extent to which buffering agents such as carnosine, bicarbonate and intracellular fluid can be trained has yet to be determined. This is not surprising given the lack of knowledge of the factors limiting muscular fatigue and the relative importance of known buffering agents. If it is accepted that training does positively influence the action of buffering agents, then it is necessary to consider the types of training necessary to maximize such effects. The extent to which variations in work duration and frequency influence acid-base regulation also remains unclear.

It is not clear whether lactic acid tolerance training increases the pain threshold, increases tissue glycogen reserves or glycolytic enzymes, increases the alkaline reserves of the tissues, facilitates a more rapid release of lactate from the muscles into the bloodstream or merely increases muscle bulk relative to blood volume (Shephard, 1990).

The exercise intensity adopted by the rower will be determined by the metabolic clearance rate (lactate turnover rated divided by the blood lactate level) and the rower's capacity to tolerate a high blood lactate concentration. It would appear that the adoption of an even pace race strategy in rowing represents a strategy of constant power production at an intensity where maximal muscular lactate values are achieved on the finish line. That is, after reaching maximal oxygen uptake in approximately the first 90 seconds of the rowing effort, the rower will undergo a constant rate of "oxygen deficit accumulation" to the extent that the maximum "oxygen deficit" possible in 6 minutes of exercise is achieved. Maximal blood lactate levels should be apparent at the conclusion of an even pace rowing effort thereby, giving some indication of intensity of effort. However, blood lactate measures are at best, a crude, qualitative indication of the lactate production rate given the numerous variables that interpose between muscle glycolysis, the appearance of a given concentration of lactic acid in the bloodstream and its eventual removal (Sephard, 1990). Blood lactate measures have been shown to be somewhat variable in rowing (Astrand and Rodahl, 1977; Hagerman et al. 1979; Secher, 1983) and this variability may have been due to a number of factors including variations in exercise intensity, diet, state of training, and the degree of activation of type IIa muscle fibres. It is necessary therefore, to be somewhat sceptical about the value of the information that can be obtained from blood lactate measures. How then may even pace race strategy be more accurately quantified?

From a biomechanical perspective, the utilization of an even pace rowing strategy would require the rower to row at a (near) constant velocity. Given the same average velocity, this strategy would require a lower power output than would be necessary should the rower adopt the traditional "U" shaped pattern of power output where the velocity varies considerably (Nigg, 1985; Di Prampero, 1986). Improvements in performance might well be reflected in a more constant pattern of power output along with increases in power output.

Fluctuations in velocity would lead to changes in viscous drag since

$$D_V = 0.5C_VV^2A \tag{14}$$

where

$C_V$ = coefficient of viscous drag

$A$ = wetted area of boat.

Viscous drag is the main force against which rowers work. The majority of the effort produced by the rower goes into overcoming viscous drag while a smaller proportion goes into overcoming air resistance (Dal Monte and Komor, 1988; Di Prampero, 1986). Given that work is proportional to the square of the velocity, a boat which travels at a velocity of 6 metres per second for half a race and at 4 metres per second for the other half would require a 4% greater work output than a boat which had a constant velocity of 5 metres per second for each half of a race (see Figure 42).

$$\begin{array}{llcl} & W & = & V^2 \times k \\ \textbf{at 6 m/sec} & W & = & 36 \times k \\ \textbf{at 4 m/sec} & W & = & \underline{16 \times k} \\ \textbf{Total} & W & = & \underline{\underline{52 \times k}} \end{array} \tag{15}$$

**at 5 m/sec** **W** = 25 x k
**at 5 m/sec** **W** = 25 x k
**Total** **W** = 50 x k

Given that the assessment and training of lactic acid tolerance still requires considerable investigation (Hahn, 1985), it would appear that the question to be addressed is whether power output during maximal rowing can be improved by adoption of a more constant pattern of power output. Therefore, phase two of this study was designed to examine whether a more constant pattern of power output reflected in a significant increase in propulsive work consistency, would result in a significant increase in mean propulsive power output per kilogram of body mass. Real time kinetic information feedback of stroke-to-stroke force-angle profile characteristics compared to a criterion force-angle profile template was used to ensure that rowers adopted a more constant pattern of power output.

### Phase two results and discussion

The results of both groups of subjects for the two dependent measures, propulsive work consistency and mean propulsive power output per kilogram of body mass, are presented in Table 12. Individual subject data ~~is~~ are presented in Appendix K.

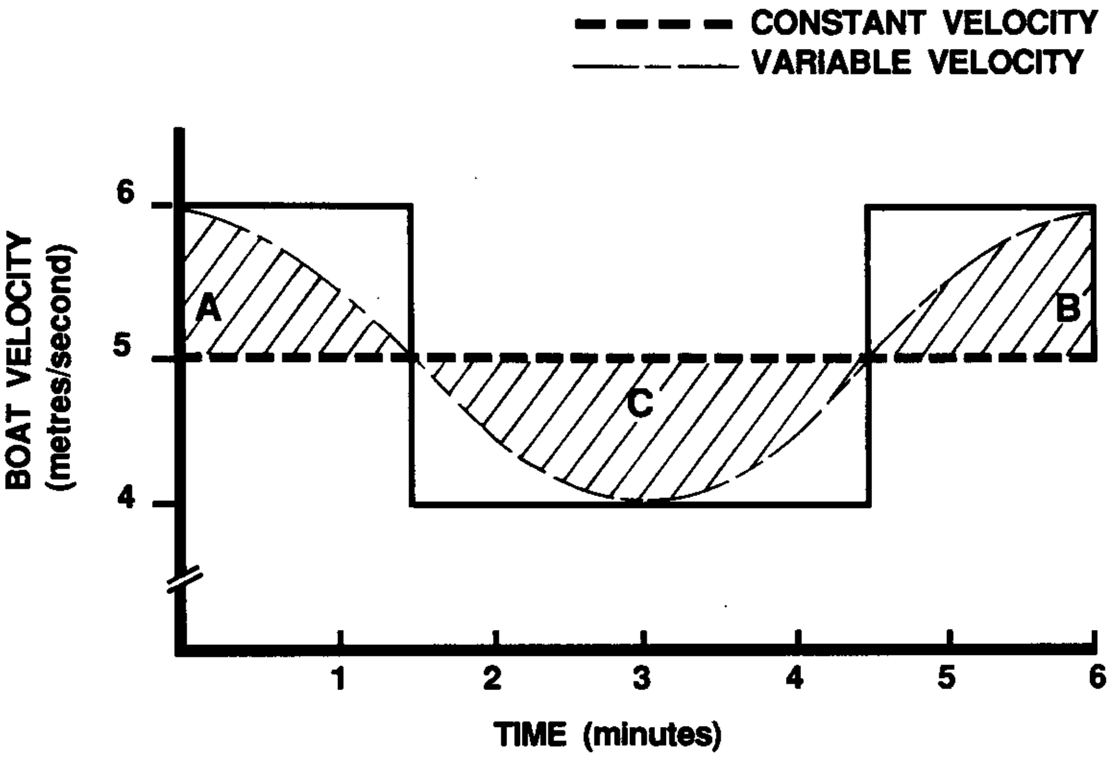


Figure 42 Work/velocity relationships in rowing
(A + B = C)

Table 12

Mean Data for Propulsive Work Consistency (PWC) and Mean Propulsive Power Output per kilogram of Body Mass (MPPO)

| Test | Dependent Measures | | Group<br>Experimental (n=17) | Control (n=17) |
|---|---|---|---|---|
| Pretest | PWC (%) | M | 88.0 | 89.6 |
| | | SD | 5.7 | 7.2 |
| | MPPO (watts) | M | 3.61 | 3.44 |
| | | SD | 0.37 | 0.50 |
| Posttest | PWC (%) | M | 91.8 | 87.1 |
| | | SD | 4.6 | 7.6 |
| | MPPO (watts) | M | 3.72 | 3.35 |
| | | SD | 0.40 | 0.67 |

Phase two of this study involved two groups of subjects who were compared with respect to measurement on two dependent variables, propulsive work consistency and mean propulsive power output per kilogram of body mass. Both groups were measured twice, the first measurement served as the pretest, the second as the posttest. Half of the subjects were randomly assigned to the experimental condition whilst the other half were assigned to the control condition. Dependent variable measurements were collected at the same time for both groups. All subjects completed the pretest and posttest. As phase two of this study involved a single independent variable and two dependent variables, a single factor multivariate analysis of covariance was performed on the data.

As well as permitting a test of the possible interactions among multiple criteria, this analysis procedure also statistically matched the subjects in the experimental and control groups on the pretest scores. Therefore, posttest differences between the means of the experimental and control groups were analyzed after taking into account and making appropriate statistical adjustments for initial differences on the pretest.

Analysis of covariance is generally employed (a) to increase precision in random-groups experiments, (b) to remove bias when subjects cannot be randomly assigned to treatment conditions, and (c) to remove variation due to unwanted factors. Analysis of covariance acts as a form of indirect (statistical) control of extraneous variability whereby the assessment of the effect of the independent variables is made more precise by partitioning out the amount of variability in the final score accounted for by the covariate (Rothstein, 1985).

In situations where the measurements on the covariate(s) are obtained prior to presentation of the treatment, an alternative research strategy is to use the covariate to form homogeneous groups of test units (blocks), and to analyze the data with a randomized blocks design analysis of variance procedure (Wildt and Ahtola, 1978). For the purposes of phase two of this study it was not possible to form homogeneous groups of test units based on both of the dependent variables and as the interdependence between these two variables was central to this study, it was necessary to use the indirect control of extraneous variance provided by the analysis of covariance rather than the direct control provided by a randomized blocks design.

The multivariate analysis of covariance test of the significance of the regression of the dependent variables on the covariates indicated significant information for both dependent variables ($F[4,58]=21.96$, $p<.001$) and for propulsive work consistency ($F[2,30]=8.45$, $p<.01$) and mean propulsive power output per kilogram of body mass ($F[2,30]=47.49$, $p<.001$) when considered separately. The multivariate analysis of covariance also indicated a significant main effect for subject groups ($F[2,29]=5.40$, $p<.02$) indicating that the posttest scores for propulsive work consistency and mean propulsive power output per kilogram of body mass when considered together were significantly higher for the experimental group than the control group. When considered separately, the posttest scores also indicated significantly higher values for the experimental group as compared to the control group for propulsive work consistency ($F[1,30]=9.82$, $p<.01$) and mean propulsive power output per kilogram of body mass ($F[1,30]=4.20$, $p<.05$).

Table 13 summarizes the multiple analysis of covariance for both dependent measures for (a) the significance of the regression of the dependent variables on the covariates, and (b) the main effect for subject groups (that is, the effects of the *independent* variable). Summary statistics for all subjects for all variables are outlined in Table 14 while summary statistics for the experimental and control groups are outlined in Table 15.

**Table 13**
**Summary of the Multiple Analysis of Covariance for the Dependent Measures**

| Effect | Variables | Statistic | F | df | p |
|---|---|---|---|---|---|
| Covariates | | | | | |
| | All | LRATIO (0.16) | 21.96 | 4,58 | *** |
| | PWC | MS (2.29) | 8.45 | 2,30 | ** |
| | MPPO | MS (3.75) | 47.49 | 2,30 | *** |
| Main: Subject Groups | | | | | |
| | All | TSQ (11.17) | 5.40 | 2,29 | * |
| | PWC | MS (2.65) | 9.82 | 1,30 | ** |
| | MPPO | MS (0.33) | 4.20 | 1,30 | * |

*** $p<.001$, ** $p<.01$, * $p<.05$
LRATIO = Wilks' lambda likelihood ratio statistic, MS = mean square,
TSQ = Hotelling's T-squared

**Table 14**
**Summary Statistics for all Subjects**

| Variable | Mean | Error | SD | Max | Min |
|---|---|---|---|---|---|
| Pretest PWC | 88.8 | 1.11 | 6.45 | 96.3 | 71.9 |
| Posttest PWC | 89.5 | 1.14 | 6.65 | 97.6 | 66.8 |
| Pretest MPPO | 3.52 | 0.76 | 0.44 | 4.28 | 2.77 |
| Posttest MPPO | 3.54 | 0.99 | 0.58 | 4.47 | 2.01 |

**Table 15**
**Summary Statistics for Subject Groups**

| Group | Variable | Mean | Error | SD | Max | Min |
|---|---|---|---|---|---|---|
| Experimental (n = 17) | | | | | | |
| | Pretest PWC | 88.0 | 1.39 | 5.73 | 95.9 | 75.1 |
| | Posttest PWC | 91.8 | 1.11 | 4.56 | 97.6 | 82.6 |
| | Pretest MPPO | 3.61 | 0.09 | 0.37 | 4.28 | 2.77 |
| | Posttest MPPO | 3.72 | 0.10 | 0.40 | 4.47 | 2.69 |
| Control (n = 17) | | | | | | |
| | Pretest PWC | 89.6 | 1.74 | 7.18 | 96.3 | 71.9 |
| | Posttest PWC | 87.1 | 1.85 | 7.64 | 94.2 | 66.8 |
| | Pretest MPPO | 3.44 | 0.12 | 0.50 | 4.28 | 2.80 |
| | Posttest MPPO | 3.35 | 0.16 | 0.68 | 4.35 | 2.01 |

Graphical representations of the results are outlined in Figures 43 and 44.

As both groups had the same number of subjects, homogeneity of variance was assumed. Tests indicated that all covariates were parallel among both groups which supported assumptions of a common slope for both groups for propulsive work consistency (_F_[2,28]=1.35, _p_>.05) and mean propulsive power output per kilogram of body mass (_F_[2,28]=1.17,_p_>.05). A common slope among all groups for each covariate is assumed in tests for equality of adjusted means and zero slopes (Dixon, 1981; Huck et al. 1974). These tests did not indicate a problem with equality of slopes at the 5% level of significance.

The kinetic information feedback provided to the experimental subjects was the force and angle characteristics of each stroke which was then compared to a template of the force-angle profile which best represented the average pretest work output. The aim was to assist the experimental subjects to achieve a more constant pattern of power output (reflected in an increase in propulsive work consistency) and a higher mean propulsive power output per kilogram of body mass.

A significant 4.32% (an actual increase of 3.8 expressed as a percentage of 88.0) increase in propulsive work consistency indicated that the experimental group was able to utilize the kinetic information feedback to effect a more constant pattern of power output. An

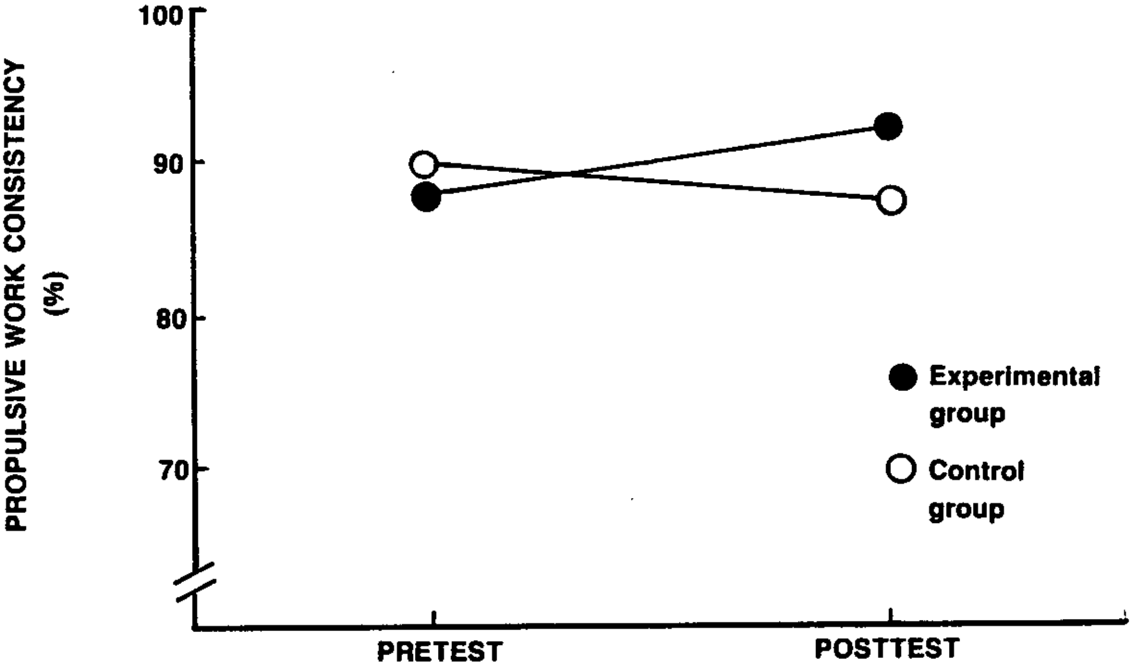


Figure 43 Pretest and posttest values for mean propulsive work consistency

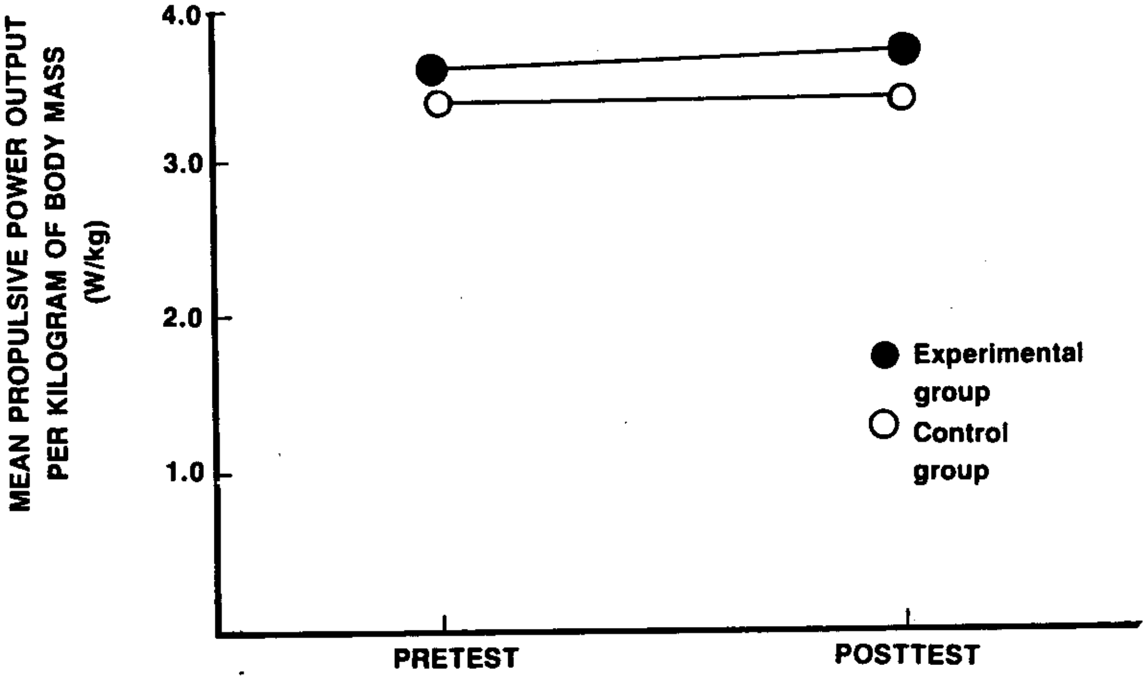


Figure 44 Pretest and posttest values for mean propulsive power output per kilogram of body mass

increase in stroke rate from pretest to posttest of only 0.04% indicated that the experimental subjects maintained a more constant force-angle profile rather than rely on stroke rate variation to maintain propulsive power output by compensating for any inability to match the criterion template.

There are two ways in which propulsive power output can be increased, the first by an increase in the area under the force-angle profile curve and the second by an increase in the stroke rate. The variables which determine propulsive power output are oar force, oar angle and time/per stroke. With instantaneous force values converted to torque values, work done was calculated as the product of the torque values and the change in oar angle, while power output was the quotient of the work done and the time. Time/per stroke is inversely proportional to stroke rate, therefore it was important to ensure that stroke rate was not a confounding variable given that it was intended that the experimental subjects control their power output by matching the criterion template. This argument assumes constant work/per stroke. In practice an increase in stroke rate is usually achieved by a decrease in recovery time leaving drive time constant thus supporting this case.

By providing stroke rate feedback every 20 seconds, as is traditional in rowing ergometer testing, restraint was placed on the time factor which allowed the rowers to control the force and angle by matching the criterion template. The stroke rate could have been more strictly controlled via mechanical means such as a metronome, however, it is highly unlikely that the 3.0% increase in mean propulsive power output per kilogram of body mass was due to the 0.04% increase in stroke rate given that the increase in mean propulsive power output per kilogram of body mass was 75 times greater than the increase in stroke rate. On the other hand, the 3.0% increase in mean propulsive power output per kilogram occurred in concert with a 3.0% increase in peak force and a 0.6% increase in stroke length (see Table 16).

**Table 16**
**Between Test Variations in Stroke Rate, Stroke Length and Peak Force for the Experimental Group**

| Test | Variables | Mean | Error | SD | % Change |
|---|---|---|---|---|---|
|  | Stroke rate (/min) | 32.100 | 0.58 | 2.39 | - |
| Pretest | Stroke length (deg.) | 80.3 | 1.12 | 4.63 | - |
|  | Peak force (N) | 732.3 | 22.50 | 92.79 | - |
|  | Stroke rate (/min) | 32.112 | 0.59 | 2.43 | 0.04 |
| Posttest | Stroke length (deg.) | 80.8 | 1.00 | 4.11 | 0.62 |
|  | Peak force (N) | 754.5 | 21.93 | 90.40 | 3.03 |

Between test variability of scores for stroke rate, stroke length (oar angle) and peak force were expressed as a proportion of their means by the coefficient of variation (Yang and Winter, 1983).

$$\text{Coefficient of variation (CV)} = (\text{SD}/\text{mean}) \times 100\% \qquad (16)$$

Derivation of the coefficient of variation involved calculation of individual subject means and standard deviations for the 13 sets of data samples for each variable for each test. Group means of these values were then derived and coefficients of variation determined for between tests analysis. This analysis indicated that the coefficient of variation for stroke rate decreased by 1.3% from pretest to posttest while the coefficients of variation for stroke length and peak force for the same period decreased by 3.7% and 33% respectively. These findings indicated that as the stroke rate was all but constant, the increase in mean propulsive power output per kilogram of body mass was due to a change in the area under the curve of the force-angle profile.

The coefficient of variation for peak force changed by a much greater amount (33%) than the increase (4.32%) in propulsive work consistency. This difference may be explained in terms of the experimental subjects adopting a more consistent within sample (stroke-to-stroke) peak force. The only possible accidental contribution to propulsive work consistency would be an out-of-phase fluctuation in peak force and stroke rate within a test which would serve to "even out" the work done. However, the maximum contribution that such an occurrence could make to propulsive work consistency for any subject would be equal to a change in the coefficient of variation for stroke rate, namely 1.3%. Figure 45 indicates the in-phase fluctuation of peak force and stroke rate typical of an experimental subject (PC) having obtained a higher

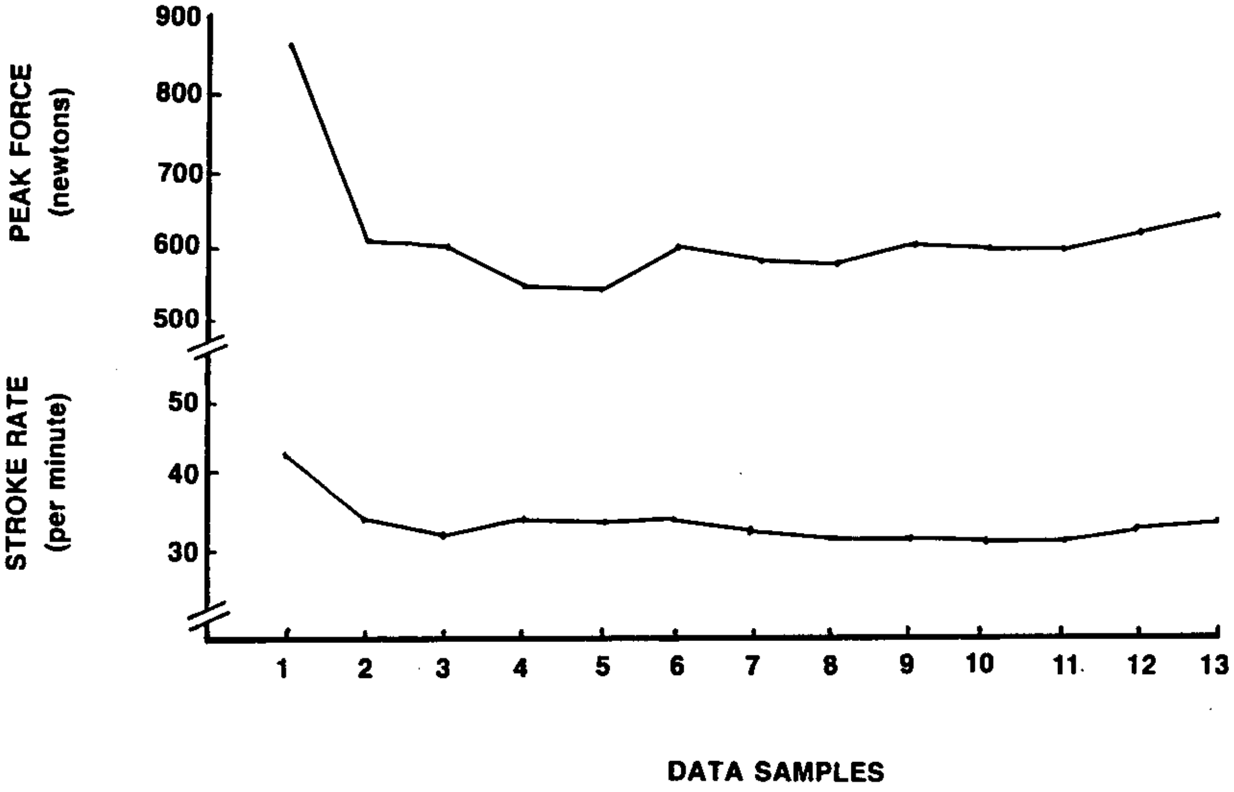


Figure 45 Posttest peak force and stroke rate fluctuations for subject PC

level of propulsive work consistency (7.8%) by adopting a more consistent stroke-to-stroke peak force. The variation in peak force between data sample one and two in this example was due to the isometric force necessary to begin movement of the ergometer fan. The analysis system recorded only the peak force. Determination of mean peak force would eliminate the confounding effect of one aberrant stroke.

Therefore, as hypothesized, the provision of stroke-to-stroke force-angle profile feedback in concert with the criterion template did lead to significant increases in propulsive work consistency and mean propulsive power output per kilogram of body mass. The coefficients of variation for stroke rate, peak force and stroke length indicated that the experimental subjects used the kinetic information feedback to maintain a more constant pattern of power output and to increase propulsive power output.

These results indicate support, from a biomechanical perspective, for the even pace or "best performance" race strategy proposed by Klavora (1979a; 1982b) for crews engaged in qualifying trials for national crew selection or when matched against obviously superior opposition. This race strategy is characterized by crews adopting a constant boat velocity requiring individual rowers to produce a constant pattern of power output which would be reflected in a high level of propulsive work consistency. The results of phase two of this study indicated that a significant increase in propulsive work consistency results in a significant increase in mean propulsive power output per kilogram of body mass.

Of the variables examined in phase one of this study, mean propulsive power output per kilogram of body mass was the most effective discriminator between rowers of differing ability levels while propulsive work consistency was the least effective discriminator. Therefore, it would appear that rowing performance may be enhanced by increasing mean propulsive power output per kilogram of body mass via a more constant level of power output as reflected in a significant increase in propulsive work consistency.

The most significant adjustment to the experimental condition was in the pattern of force application, that is, there was less variability in the peak force, the mean values of which increased from 732.3 newtons to 754.5 newtons. The experimental subjects made less adjustment for stroke length, which increased by 0.5 degrees. Therefore, the kinetic information feedback was used to scale the level of force production and, to a lesser extent, to define the angle through which the force was applied. This finding was similar to that of Newell and Carlton (1987), who determined that the application of a force-time template appeared primarily to assist subjects to scale the level of force production in a finger press isometric task rather than to define the force-time profile itself.

By presenting the stroke-to-stroke force-angle profile information in conjunction with a representation of the criterion (the template) the subjects were not only able to view a representation of the response just produced (descriptive information) but were also able to determine the degree and nature of any variation from the task criterion by comparison with the template (prescriptive information) (Newell et al. 1985b).

It has been suggested (Newell and Carlton, 1987) that the application of information feedback should be based on an awareness of the organismic and task constraints that are apparent in the motor performance situation. Research on kinetic (Newell et al. 1985b) and kinematic (Newell et al. 1983) information feedback has demonstrated the importance of matching the augmented information feedback to the administered task criterion. Newell and Carlton (1987) have suggested that it is the interaction of the organismic and task constraints that specifies the appropriate augmented information for skill learning.

Where the organismic constraints involve prior subject knowledge of the criterion, Newell and Carlton (1987) found that a criterion template plus a force-time trace was not significantly beneficial when compared to a force-time trace and discrete knowledge of results information of absolute integrated error. It was proposed, that in situations where the task constraints are familiar that the presentation of augmented information feedback is of greater value to the subject than the criterion information. On the other hand, the prescriptive criterion information was believed to be of assistance when the task constraints are unfamiliar.

For the purposes of this study it was assumed that club level rowers would have sufficient cognitive representation (Carrol and Bandura, 1982) of the relationships between the force-angle profile and body, arm and oar handle movements. However, it was not possible to assume that the experimental subjects would be able to use their knowledge of the parameters of the force-angle profile to effect a more constant pattern of power output and an increase in mean propulsive power output per kilogram of body mass. Given that any lack of understanding would have acted as an organismic constraint (Newell and Carlton, 1987), the experimental subjects were provided with the criterion template in order to facilitate the interaction between the augmented criterion and the stroke-to-stroke feedback and the task and organismic constraints.

It may well be that the interaction between the criterion template and the stroke-to-stroke force-angle profile is a more useful form of kinetic information feedback than a digital display indicating average power output. The digital display on the widely utilized Concept II rowing ergometer indicates the average power output to any particular stage of an ergometer test. A rower who produces a relatively higher power output at the beginning of a rowing effort and who then generates a constant but lower power output is presented with a progressively decreasing digital reading.

Hahn et al. (1988) found that this form of information feedback confused rowers and the authors called for information feedback of average power output or number of flywheel revolutions for discrete blocks of time for example, every 30 seconds. However, this procedure would result in a longer inter-response interval and might well require a greater degree of information feedback transformation than a stroke-to-stroke comparison with a criterion template. It may be argued that the need for information feedback transformation may be significantly reduced or even eliminated by the use of kinetic information feedback presented concurrently with and in the same fashion as a model of the criterion response. This process would enable the rower to focus on the necessary information and to reduce the impact of extraneous response information (Newell and Walter, 1981). The provision of concurrent information feedback may allow the rower to accumulate a number of stroke cycles and feedback presentations into an information unit that describes the relationship between the characteristic movements of the rowing stroke and the information feedback. Broker et al. (1989) were of the opinion that this strategy allows performers of continuous tasks such as cycling and rowing, to be immune to the deleterious effects of frequent feedback, such as an inability to make one-to-one associations between individual strokes and the criterion template.

Schmidt (1988) stated that kinetic information feedback has the potential to be of considerable value in skill learning. However, there has been limited research into the learning versus performance effects of kinetic information feedback. Changes in subject behaviour from a pretest to a posttest situation may lead one to infer that learning has taken place. However, these changes may be due to a variety of extraneous factors such as a physiological adaptation to training (as may occur in a multiple repeated measures design), the level of intrinsic motivation and the expectation of reward (Leavitt and Weir, 1990). There is also a poor relationship between the degree of performance change and the degree of learning with the amount of learning not always being indicated in the performance scores (Schmidt, 1972).

Newell et al. (1985b) were able to demonstrate that the effects of kinetic information feedback were relatively permanent in that they persisted during a short-term no-feedback retention test. The extent to which rowers can learn to adopt a more constant pattern of power output may be determined by the utilization of a transfer research design. A transfer research design for the current study might involve both groups of subjects being exposed to a common level of the independent variable (feedback or no feedback) after a period of time removed from the task to disperse any transitory effects of the independent variable. In a situation where the posttest differences between the two groups ~~is~~ are replicated it would suggest that the effect of the independent variable was "relatively permanent" so that the independent variable can be seen as influencing the learning of the task. Where the posttest differences between the groups disappears, it may be suggested that the influence of the independent variable is temporary at best and has no effect on learning. A scenario where only a portion of the posttest group differences vanishes would indicate that the independent variable affects both performance (temporarily) and learning (Salmoni et al. 1984; Schmidt, 1982; 1988).

In the conduct of a transfer research design it is important to ensure that the feedback conditions prevailing during initial learning are present during the retention test. Lack of control in this area could see environmental factors influence the final performance scores and the degree of confidence one has in the extent of learning (Leavitt and Weir, 1990).

Where the results of such studies indicate that there is a relatively permanent effect resulting from kinetic information feedback there would not only be important practical considerations but it is also likely that the form of kinetic information feedback that was effective was that aspect of the movement response controlled by the subject. Therefore, this type of motor learning research could provide greater understanding about movement control (Salmoni et al. 1984).

An examination of intra-test dynamics from an "ecological" or "action" perspective (Bernstein, 1967; Meijer and Roth, 1988; Reed, 1982; 1988; Whiting, 1984) might well result in an understanding of the extent to which the rower is able to use the kinetic information feedback to co-ordinate the rhythmic actions of the rowing stroke. The ecological or action perspective focusses on the action itself and aims to contract the form of an action to the smallest representation of its dynamics. The degrees of freedom associated with the action are reduced by the development of co-ordinative or synergistic structures comprising combinations of muscles which behave as a single unit for a certain action (Lockwood and Parker, 1989). The force-angle profile may serve as a graphical representation of the overall characteristics of the rowing movement being the resultant output of a certain number of synergies. The force-angle profile could be seen as a representation of the degree to which the rower has learnt to integrate the synergies into the output. Rowers unable to co-ordinate the rowing action with the kinetic information feedback might demonstrate a less stable force-angle profile output representing a lack of synergy and decreased dynamic organization. Under these circumstances the lack of co-ordination in rhythmic actions may result in a more random contribution from the musculature leading to a "noisier" force-angle profile and influencing stroke smoothness as reported in the discriminant analysis. It is possible that the "ecological" or "action" perspective may also be of value in transfer research designs.

Biomechanics research in rowing occurs not only in university laboratories but also in national and state sports institutes and in many rowing clubs. In Australia, it would appear that this research is fragmented and therefore, directionless. For example, research at the club level is often conducted by interested professionals, usually with an engineering background, and other rowing enthusiasts who are largely removed from the human movement/sports science community. Also, the human movement/sports science community, hampered by a lack of funds and a significant research culture, finds it difficult to maintain appropriate contact with the rowing community.

Researchers in the biomechanics of rowing grapple with a complex movement pattern and the necessity to combine optimal human movement with high quality sophisticated equipment for superior performance to occur. While the coaching literature recognizes the need for coaches to be cognizant of the biomechanics of rowing, the extent to which this information is utilized in the coaching process, for example, in crew selection and fault analysis, is not so apparent.

As is the case in many sports, neophyte rowing coaches undergoing the coaching accreditation process have to attempt to integrate a variety of biomechanical principles into a "whole" that is the rowing skill. This study demonstrates how a coach may begin at a familiar point namely, the force on the oar handle and the angle that the oar moves through, and then follow the manner in which the force and angle characteristics influence other rowing performance factors. Examination of the force-angle profile allows the coach to identify those biomechanical factors limiting a rower's performance and to recognize the sort of process needed to determine the best available rowing technique for a given rower. This process should also encourage the rowing coach to consider the desirability of requiring rowers to adopt a particular rowing style simply because it is "recognized" as being "superior" to other styles. In other words, what is biomechanically efficient for one rower may prove to be relatively deleterious to another despite similarities in physiological, anthropometric and psychological characteristics. Similarly, the adoption of a particular race strategy not only calls for an accurate assessment of the quality of the opposition but it also demands a clear understanding of the role that biomechanical factors play in influencing the ultimate goal of competitive rowing that is, the final race time.

## Summary

### Phase one

Phase one of this study considered the differences between three groups of rowers with respect to selected biomechanical performance variables namely, mean propulsive power output per kilogram of body mass, propulsive work consistency, stroke-to-stroke consistency and stroke smoothness. A pooled within-groups correlation analysis indicated low correlations between corresponding pairs of variables which in turn, indicated the relatively independent origin of the four biomechanical performance variables chosen to represent rowing capacity and skill.

Discriminant function analysis indicated the presence of two discriminant functions. Function one indicated that mean propulsive power per kilogram of body mass made the greatest contribution to scores on that function followed by propulsive work consistency, stroke-to-stroke consistency and stroke smoothness. On Function two, stroke-to-stroke consistency made the greatest contribution closely followed by mean propulsive power output per kilogram of body mass with a lesser contribution from stroke smoothness and only a minor contribution from propulsive work consistency.

Both discriminant functions clearly indicated the importance of mean propulsive power output per kilogram of body mass as a discriminating variable. The skill based variables, stroke-to-stroke consistency and stroke smoothness, were of greater relative importance to Function two than Function one. Function one was the most powerful discriminator providing the most information about the differences between the groups of rowers. However, the derived discriminant functions were significant as a set.

Classification procedures correctly placed 88.9% of the novice level rowers, 73.9% of the state level rowers and 100% of the national level rowers. In all, 82.93% of the rowers were correctly classified into their respective groups by the weighted discriminant scores. The percentage of correct classifications proved to be the most intuitive measure of the amount of discrimination provided by the biomechanical performance variables.

Stepwise discriminant analysis included the biomechanical performance variables in the order: mean propulsive power output per kilogram of body mass, stroke-to-stroke consistency, stroke smoothness and propulsive work consistency. The mean data for the three groups of rowers showed a positive relationship between performance level and each of the biomechanical performance variables. It was also apparent that the degree of variability within a group of rowers decreased as the performance level increased. While all four variables made a significant contribution to discrimination between the groups of rowers, propulsive work consistency was the least effective discriminator. This finding would seem to indicate that male rowers of all ability levels utilize skill based biomechanical performance variables such as stroke-to-stroke consistency and stroke smoothness in maximizing propulsive effort rather than assume a more effective pattern of power output.

The results of phase one of this study confirm that male rowers of all ability levels adopt a "U" shaped pattern of power output which reflects a lack of consistency in work output. It is generally believed that this pattern of energy expenditure is physiologically inefficient which has resulted in a proposal that crews adopt an even pace or "best performance" strategy when competing against obviously superior crews or when attempting to lower set times in qualifying trials for national crew selection.

The physiological rationale for adoption of the even pace strategy is related to maximization of the aerobic energy source with maximal "oxygen debt" occurring in the last stroke of the race. This rationale appears to be based on the classical concept of metabolite accumulation during heavy exercise. In other words, if the pace is too difficult the rower will enter "oxygen deficit" which will result in a build up of lactic acid causing muscular fatigue. During recovery the "oxygen debt" is seen as being repaid with lactate being reconverted to glycogen. However, the lactic acid explanation for muscular fatigue is no longer universally accepted. Lactate is a dynamic metabolite during both rest and exercise and it acts to maintain blood glucose through gluconeogenesis and to shuttle oxidizable substrate from areas of high glycogenolytic rate to areas of high cellular respiration.

Lactic acid accumulation occurs when lactate production exceeds removal. At a physiological pH, lactic acid dissociates hydrogen ions which causes a decrease in pH. Lower pH levels inhibit phosphofructokinase and slow glycolysis and muscular function. The exercise intensity adopted by the rower will therefore depend, upon the metabolic clearance rate and the rower's capacity to tolerate a high blood lactate concentration. The adoption of an even pace race strategy in rowing requires the rower to develop a constant power output at an intensity where maximal lactate values are achieved on the finish line.

There are many factors that influence muscle glycolysis, lactic acid concentration levels and the eventual removal of lactate. These factors include exercise intensity, diet, state of training, buffering capacity and adaptation to aerobic training regimes. There is some doubt as to the value of the information provided by blood lactate readings, therefore it is difficult to quantify the stated advantages of the even pace race strategy in rowing.

From a biomechanical perspective the adoption of an even pace race strategy would require the rower to row at a constant velocity. Fluctuations in velocity would lead to changes in viscous drag. As viscous drag is the main force against which rowers work and given that work is proportional to the square of the velocity, rowing at a constant velocity would require a lower work output. While improvements in rowing performance may not be accurately determined by physiological means they may well be reflected in a more constant pattern of power output coupled with increased power output. Therefore, phase two of this study aimed to determine whether a more constant pattern of power output, reflected in a significant increase in propulsive work consistency, would result in a significant increase in mean propulsive power output per kilogram of body mass. Real-time kinetic information feedback of stroke-to-stroke force-angle profile characteristics compared to a criterion force-angle profile template was used to ensure that a more constant pattern of power output was adopted.

### Phase two

Single factor multivariate analysis of covariance indicated significant information for both dependent variables, considered together or separately, in relation to the regression of the dependent variables on the covariates. The pretest scores for propulsive work consistency and mean propulsive power output per kilogram of body mass were utilized as the covariates. The multivariate analysis of covariance also indicated a significant main effect for subject groups indicating that the posttest means for propulsive work consistency and mean propulsive power output per kilogram of body mass, when considered together and separately, were significantly higher for the experimental group than the control group.

The significant 4.2% increase in propulsive work indicated that the experimental group was able to utilize the kinetic information feedback to effect a more constant power output. A 0.04% increase in stroke rate indicated that the experimental group maintained a more constant force-angle profile rather than rely on stroke rate variation to maintain propulsive power output. The 3.0% increase in mean propulsive power output per kilogram of body mass was 75 times greater than the increase in stroke rate. However, the increase in mean propulsive power output per kilogram of body mass was accompanied by a 3.0% increase in peak force and 0.6% increase in stroke length.

Between-test variability of scores for stroke rate, stroke length and peak force indicated that the coefficient of variation for stroke rate decreased by 1.3% while the stroke length and peak force coefficients of variation decreased by 3.7% and 33% respectively. These results indicated that as the stroke rate was essentially constant, the increase in mean propulsive power output per kilogram of body mass was due to a change in the area under the curve of the force-angle profile. It would appear that the experimental subjects adopted a more consistent level of peak force from stroke-to-stroke.

The results of phase two of this study indicated that rowers are able to utilize kinetic information feedback to maintain a more constant pattern of power output and to increase mean propulsive power output per kilogram of body mass. These results provide support, from a biomechanical perspective, for the even pace or "best performance" race strategy in rowing. This race strategy calls for a constant boat velocity requiring rowers to produce a constant pattern of power output which in turn is reflected in a high level of propulsive work consistency. The results of phase two of this study suggest that a significant increase in propulsive work consistency results in a significant increase in mean propulsive power output per kilogram of body mass. Given that phase one of this study determined that mean propulsive power output per kilogram of body mass was the most effective discriminator between groups of rowers it would appear that rowing performance may be enhanced by increasing mean propulsive power output per kilogram of body mass.

It is apparent that club level rowers are able to use kinetic information feedback to scale the level of force production and the angle through which the force is applied. Stroke-to-stroke force-angle profile information was presented in conjunction with a criterion force-angle profile which represented the average pretest work output. This enabled the subjects to view a representation of each response and to determine the degree and nature of any deviation from the task criterion. It was assumed that this prescriptive criterion information would facilitate interaction between the criterion and the stroke-to-stroke kinetic information feedback and serve to reduce the influence of task and organismic constraints. It may be argued that this form of information feedback results in a significant reduction, or elimination, of the need for information feedback transformation. This would enable the performer to focus on the relevant information thus reducing the influence of extraneous information.

While the results of phase two of this study indicated that kinetic information feedback acts to enhance performance, its role in skill learning has yet to be established. The evaluation of kinetic information feedback in research designs that allow firm conclusions regarding the relatively permanent effects of such feedback would not only have practical implications, but would also indicate those responses that the subject controls. This motor learning research could provide valuable information regarding movement control. Assessment of the degree of development of co-ordinative or synergistic muscular structures may help to examine the extent to which performers utilize kinetic (or kinematic) information feedback to control movement. The degree of co-ordination in rhythmic actions may also indicate the degree of motor learning.

Biomechanical analysis in rowing is a challenging task given the complex movement pattern and the need to combine a highly refined movement pattern with sophisticated equipment. Research in this area is fragmented and represents the rather disparate interests of those concerned. Consequently, the dissemination of biomechanical information to coaches does little more than appraise them of certain biomechanical principles underlying the rowing movement. It is not clear to what extent coaches are able to integrate this information in order to gain a clear understanding of the demands of competitive rowing and the needs of the rower.

This study has shown that examination of the force-angle profile may allow identification of those biomechanical factors which limit a rower's performance and may assist the coach to recognize the processes involved in the determination of the best available rowing technique for a given rower.

# Chapter 5

# SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

## Summary

The coaching education program adopted by the Australian Rowing Council in 1981 involves consideration of many of the features of human movement/sports science disciplines including selected biomechanical principles along with the technical and skill based aspects of competitive rowing. The extent to which rowing coaches can use this information to identify limiting factors in rowing and to enhance rowing performance is not readily apparent.

Biomechanical analysis in rowing involves consideration of the kinematics and kinetics of the boat-oar-rower mechanical system. The coaching of the rowing stroke has traditionally involved visual analysis of the kinematic parameters which represent the "aesthetics" of the rowing action. Visual analysis of these parameters may not provide sufficient information to accurately quantify or analyze the rowing stroke. A range of kinetic parameters influence these kinematic parameters and overall rowing performance. Kinetic parameters influence the boat, the oar and the rower, however, the oar as the main propulsive element, has received the most research attention. Oar forces comprise the reaction force at the oar lock, the longitudinal and transverse components of the forces acting on the blade and the force exerted by the rower on the handgrip of the oar.

Oar force analysis in rowing involves consideration of force-time, oar-angle-time and force-oar angle parameters. Rowers have been found to possess highly individual force-time curves which can be used to assess rowing technique or to select or balance crews. Rowing performance depends largely on the magnitude of the force applied to the oar and the angle (or distance) through which that force acts. A plot of this relationship, the force-angle profile, may be used to examine stroke length, peak force, peak force position, inertial force, catch force, finish force, work output, stroke smoothness, stroke-to-stroke consistency and propulsive work consistency. Despite revealing a range of features of great value to the assessment of rowing capacity and skill, the force-angle profile has received little research attention.

Performance in a particular sport is related to a set of identifiable performance variables each of which has a particular contribution to make to effective performance in that sport. While there has been considerable interest in the relative importance of a variety of performance, anthropometric, physiological and psychological variables to maximal rowing performance there has been relatively little examination of the role of biomechanical performance variables. Of particular interest in this study were those biomechanical performance variables derived from an analysis of oar force and oar angle data.

The biomechanical performance variables included the work capacity measures mean propulsive power output per kilogram of body mass and propulsive work consistency and the skill measures stroke-to-stroke consistency and stroke smoothness. This study set out to determine the relative importance of these biomechanical performance variables to maximal rowing performance and to examine ways of using this information in the coaching process.

Phase one of this study was conducted to determine the extent to which the biomechanical performance variables could be used to accurately discriminate between rowers of differing ability levels. Due to the unique work output pattern utilized by rowers it was hypothesized that propulsive work consistency would be the least effective discriminator between groups of rowers.

The objective of competitive rowing is to cover the 2,000 metre race distance in the fastest possible time. Competitive rowing is considered to be one of the most demanding continuous endurance sports requiring very high levels of aerobic power, muscular strength and endurance and a significant contribution from the anaerobic energy pathways. While it is considered that the adoption of a constant velocity throughout the race would be the most economical way to undertake the race, rowers almost invariably adopt a pacing strategy where the velocity varies considerably. This pacing strategy results in power output decreasing relative to blood lactate accumulation indicating a lack of consistency in work output.

It has been suggested that rowers adopt an even pace or "best performance" race strategy when attempting to lower qualifying times in national selection trials or when opposing crews of superior ability. This strategy is based on maximization of the aerobic energy pathways with maximum "oxygen debt" and maximal lactate values occurring on the finish line. However, it is likely that the anaerobic energy pathways can make a significant contribution to maximal rowing performance. Lactate as a dynamic metabolite in both resting and exercising individuals is highly correlated to metabolic rate during exercise being the inevitable result of anaerobic glycolysis.

There is concern regarding the value of blood lactate measures as determinants of exercise intensity and the assessment and training of lactic acid tolerance still requires considerable investigation. Therefore, phase two of this study was conducted to determine whether power output during maximal rowing could be improved by ensuring a more consistent pattern of work output. It was hypothesized that kinetic information feedback of stroke-to-stroke force-angle profile characteristics compared to a criterion force-angle profile template would result in a more constant pattern of power output, as reflected in a significant increase in propulsive work consistency, and a significantly higher mean propulsive power output per kilogram of body mass.

Successful performance in competitive rowing requires a high level of movement consistency and the establishment of a highly efficient movement pattern. In the quest for maximal efficiency, the coach must provide the rower with objective information feedback for accurate error detection and correction.

Apart from practice, information feedback is the most important element of motor learning. Information feedback is used to modify performance so that particular motor behaviours can be achieved with respect to specified performance objectives. Knowledge of results has long been considered an influential form of feedback in that it allows performers to examine their efforts in relation to an externally defined goal. However, this type of feedback provides only goal related information and ignores information about how the action was completed.

Movement pattern analysis involves consideration of the kinematic and kinetic characteristics of the movement. While variables related to these characteristics are regularly assessed in sports biomechanics research, their value as information feedback has received relatively little research interest. There is growing support for the contention that kinematic and kinetic information feedback can be utilized to facilitate the acquisition and optimization of motor skills.

Therefore, a central focus of this study was to examine the effects of concurrent kinetic information feedback on biomechanical performance variables that influence maximal rowing performance.

The kinetic information feedback was provided in a visual format on the basis that visual feedback has been shown to be the more potent form of feedback by dominating other sensory modalities across a broad range of perceptual-motor activities. Visual feedback is seen as being of particular value to the experienced performer who is able to relate the feedback to a well developed cognitive representation of the task thus allowing for accurate modification of the movement pattern, calibration of the proprioceptive control mechanisms, enhanced consistency of performance and recognition of the discrepancies between conceptualization and realization of the action plan. In order to ensure the effectiveness of the visual kinetic feedback it was presented in a manner that was analogous to the desired movement, that facilitated rapid information processing and that allowed for continuous assessment of the action plan.

Phase one of this study examined the extent to which selected biomechanical performance variables, derived from oar force and oar angle data, discriminated between rowers of differing ability. Oar force and oar angle data was obtained from a 6 minute maximal rowing ergometer test undertaken by novice ($\underline{n}$=9), state ($\underline{n}$=23) and national ($\underline{n}$=9) level male rowers. Oar force was determined via an XTRAN S1W 2KN

S-beam load cell attached in series with the rope of a wheeled Repco rowing ergometer. Oar angle data was measured using a rotary potentiometer with a 10 kilohm servo potentiometer with a guaranteed linearity of 0.5%. Collected data were filtered with a cutoff frequency of 12.5 hertz and sampled for an 8 second period every 30 seconds at 25 hertz via a DT2801 analogue to digital converter (Data Translation) and was then processed by a MS-DOS microcomputer. The data collection rate was determined given a maximum frequency of 5 hertz for the rowing movement.

Processed data files for each 30 seconds of the 6 minute maximal rowing effort provided information on length of stroke (degrees), stroke rate (/min), peak force (newtons), total work (joules), total propulsive work (joules), stroke-to-stroke consistency (%), propulsive work consistency (%), stroke smoothness (%) and mean propulsive power output per kilogram of body mass (watts). The statistical procedure used to analyze the data was multiple discriminant analysis which was chosen to determine the relative ability of the four biomechanical performance variables to predict individual rowing performance levels.

Multiple discriminant analysis indicated the presence of two discriminant functions both of which gave a relatively heavy weighting to mean propulsive power output thus confirming the importance of this variable as a discriminant variable. Classification procedures correctly placed 88.9% of the novice level rowers, 73.9% of the state level rowers and 100% of the national level rowers. Overall, 82.93% of the rowers were correctly classified into their respective groups. All four biomechanical performance variables made a significant contribution to discrimination between the groups of rowers with stepwise analysis including the variables in the order mean propulsive power output per kilogram of body mass, stroke-to-stroke consistency, stroke smoothness and propulsive work consistency. The addition of propulsive work consistency last indicated that it was the least effective discriminator.

These results suggest that male rowers of all ability levels utilize a "U" shaped pattern of power output which indicates a lack of consistency in work output. The results also suggest that rather than adopt the most effective pattern of power output, rowers will make greater relative use of skill based biomechanical performance variables such as stroke-to-stroke consistency and stroke smoothness.

From a biomechanical perspective, the adoption of an even pace race strategy would require the rower to row at a constant velocity which in turn, would require a constant pattern of power output. A more constant pattern of power output, reflected in an increase in propulsive work consistency, which in turn resulted in an increase in mean propulsive power output per kilogram of body mass would serve to enhance rowing performance.

Phase two of this study was designed to examine whether mean propulsive power output per kilogram of body mass could be significantly increased by an improved level of propulsive work consistency. Real-time kinetic information feedback consisting of stroke-to-stroke force-angle profile characteristics in combination with a criterion force-angle profile template was provided to ensure that rowers adopted a more consistent pattern of work output.

Club level male rowers (N=34) volunteered to participate in this phase of the study and undertook two 6 minute maximal rowing ergometer tests separated by a 7 day period. The first test served as a pretest with the subjects following the test protocol utilized in-phase one of this study. No performance feedback was provided at the completion of the pretest. Following the pretest the subjects were randomly allocated to a control (n=17) or experimental (n=17) group. Prior to the posttest all subjects were advised of their pretest results and the strategies necessary to maximize work output via optimization of the force-angle profile.

During the posttest, the experimental subjects received kinetic information feedback in the form of a visual display of the force-angle profile for each stroke compared to a force-angle profile template which represented the average pretest work output. On taking a stroke the subject could immediately gauge the extent to which that stroke met the task criterion. The kinetic information feedback was provided uninterrupted for the duration of the warm-up and maximal work phases of the rowing ergometer test. Single factor multiple analysis of covariance (MANCOVA) was used to test for significant differences between both groups of subjects for posttest scores for propulsive work consistency and mean propulsive power output per kilogram of body mass.

The results of the MANCOVA indicated that the posttest scores for propulsive work consistency and mean propulsive power output per kilogram of body mass when considered together were significantly higher ($p<.02$) for the experimental group than the control group. When considered separately, the posttest scores also indicated significantly higher values for the experimental group as compared to the control group for propulsive work consistency ($\underline{M}=91.8, \underline{F}[1,30]=9.82$, $\underline{p}<.01$) and mean propulsive power output per kilogram of body mass ($\underline{M}=3.72, \underline{F}[1,30]=4.20$, $\underline{p}<.05$). Tests for parallelism supported assumptions of a common slope for each group of subjects for propulsive work consistency ($\underline{F}[2,28]=1.35$, $\underline{p}>.05$) and mean propulsive power output per kilogram of body mass ($\underline{F}[2,28]=1.17$, $\underline{p}>.05$).

The significant 4.2% increase in propulsive work consistency accompanied only a minor (0.04%) increase in stroke rate which indicated that the experimental subjects maintained a more constant pattern of power output rather than rely on stroke rate variation to increase propulsive power output. The significant increase in mean propulsive power output per kilogram of body mass was also accompanied by a 3% increase in peak force and a 0.6% increase in stroke length. These results indicated that as the stroke rate was essentially constant, the increase in mean propulsive power output per kilogram of body mass was due to a change in the area under the curve of the force-angle profile. It would appear that the experimental subjects were able to utilize the kinetic information feedback to scale the level of force production and thus were able to adopt a more consistent level of peak force from stroke-to-stroke.

These results provide support from a biomechanical perspective, for the even pace race strategy in rowing which is characterized by a constant boat velocity requiring rowers to produce a constant pattern of power output. This study has shown that the adoption of a constant pattern of power output may result in a significant increase in mean propulsive power output per kilogram of body mass which according to the results of phase one of this study would have positive implications for rowing performance.

## Conclusions

Within the limitations of this study, the following conclusions regarding the research hypotheses seem justified:

(1) The biomechanical performance variables mean propulsive power output per kilogram of body mass, propulsive work consistency,

stroke-to-stroke consistency and stroke smoothness effectively discriminate between rowers of differing ability levels. These biomechanical performance variables are derived from oar force and oar angle data collected during a maximal ergometric rowing effort.

(2) Of the aforementioned variables, propulsive work consistency is the least effective discriminator between rowers of differing ability levels.

(3) Kinetic information feedback of stroke-to-stroke force-angle profile characteristics compared to a criterion force-angle profile template significantly increases propulsive work consistency during maximal ergometric rowing.

(4) Rowers who utilize kinetic information feedback in order to significantly increase propulsive work consistency demonstrate a significant increase in mean propulsive power output per kilogram of body mass during maximal ergometric rowing.

## Recommendations

It is recommended that further study be conducted in the following areas:

(1) Determination of the extent to which ergometer derived biomechanical performance variables predict on-water performance at all levels of rowing performance.

(2) Examination of the effects of skill learning on biomechanical performance variables in rowing.

(3) Consideration of the extent to which gender influences the relative importance of biomechanical performance variables to rowing performance.

(4) Determination of the extent to which rowing coaches are aware of the biomechanical performance variables influencing rowing performance and the degree to which coaches can utilize knowledge of biomechanical performance variables to improve rowing performance.

(5) Analysis of the kinetic parameters contributed by the rower as an integral part of the oar-boat-rower mechanical system. That is, the forces exerted on the oar handle, the seat and the stretcher.

(6) Examination of the effects of information feedback on skill based biomechanical performance variables in rowing.

(7) Determination of the effects of kinetic information feedback on on-water rowing performance.

(8) Assessment of the effects of kinetic information feedback on the learning of rowing skills.

(9) Examination of the extent to which changes in the relative contribution of biomechanical performance variables influences the physiological cost of rowing.

(10) Analysis of the biomechanical and physiological advantages of adopting particular rowing styles and race strategies.

(11) Evaluation of the task, organismic and environmental constraints influencing skill acquisition and performance in rowing.

(12) Determination of the extent to which frequency and scheduling of kinetic and kinematic information feedback influences the acquisition and performance of motor skills.

(13) Determination of the extent to which a task criterion is necessary in the provision of kinetic and kinematic information feedback during the performance of continuous motor tasks.

(14) Consideration of the degree to which kinetic and kinematic information feedback should represent the motor performance goal or elements of the action plan.

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## PHASE ONE INFORMED CONSENT

I, ______________________________, state that I am over eighteen (18) years of age and wish to participate in a research program being conducted by Mr. Warwick Spinks.

The purpose of the research is to identify a number of biomechanical variables based on an analysis of oar force and oar angle in maximal rowing which may be used to achieve improved discrimination between rowers.

The project involves one laboratory visit of approximately 40 minutes duration. For this investigation:

(1) Height, weight, date of birth and rowing status will be recorded.
(2) A brief medical examination will be conducted.
(3) Three ECG electrodes will be attached to the chest in order to measure heart rate.
(4) A 4 minute warm-up will be conducted on the rowing ergometer.
(5) A 6 minute maximal rowing ergometer test will be conducted.
(6) The results of the maximal rowing ergometer test will be collected by a computer.

The personal risks involved are those risks normally associated with maximal work capacity tests which are, according to prior research, generally minimal.

I acknowledge that I have been informed that this procedure will benefit me personally by providing biomechanical and skill acquisition data related to my rowing capacity and ability.

I acknowledge that Warwick Spinks has fully explained to me the risks involved and the need for this research; has informed me that I may withdraw from participation at any time; and has offered to answer any inquiries that I may make concerning the procedures to be followed. I freely and voluntarily consent to my participation in this research project.

______________________________
(Signature of volunteer)

______________________________
(Signature of investigator)

______________________________
(Signature of witness
of explanation)

______________________________
(Date)

# PHASE TWO INFORMED CONSENT

I, ______________________________, state that I am over eighteen (18) years of age and wish to participate in a research project being conducted by Mr. Warwick Spinks.

The purpose of the project is to examine the effects of biomechanical feedback related to oar force and oar angle on selected work capacity measures during maximal rowing.

The project involves 2 laboratory visits each of approximately 40 minutes duration held 7 days apart. For each laboratory visit:

(1) Height, weight, date of birth and rowing status will be recorded.
(2) A brief medical examination will be conducted.
(3) Three ECG electrodes will be attached to the chest in order to measure heart rate.
(4) A 4 minute warm-up will be conducted on the rowing ergometer.
(5) A 6 minute maximal rowing ergometer test will be conducted.
(6) The results of the maximal rowing ergometer test will be collected by a computer.

Biomechanical feedback will be provided prior to the second test.

The personal risks involved are those risks normally associated with maximal work capacity tests which are, according to prior research, generally minimal.

I acknowledge that I have been informed that this procedure will benefit me personally by providing biomechanical and skill acquisition data related to my rowing capacity and ability.

I acknowledge that Warwick Spinks has fully explained to me the risks involved and the need for this research; has informed me that I may withdraw from participation at any time; and has offered to answer any inquiries that I may make concerning the procedures to be followed. I freely and voluntarily consent to my participation in this research project.

________________________
(Signature of volunteer)

________________________
(Signature of investigator)

________________________
(Signature of witness of explanation)

________________________
(Date)

## SUBJECT INSTRUCTIONS FOR PHASE ONE

Thank you for consenting to participate in this study. You will be required to complete a 6 minute maximal rowing ergometer effort at this test session. The test will be preceded by a 4 minute warm-up. The warm-up should be submaximal, that is, about 70% oar force at 24 strokes per minute. Your electrocardiogram and heart rate will be monitored continuously during the test. Data relating to stroke rate, stroke length, oar force and work done will be collected by a computer. This data will be available to you immediately following the test. Are there any questions?

You should utilize your normal pattern of work output for a maximal rowing effort. Use your normal starting procedure and once you have completed the start phase you should maintain a stroke rate of around 33 strokes per minute. Do not allow your stroke rate to fall below 31 strokes per minute. I will call your stroke rate every 20 seconds and elapsed time every 30 seconds. It is important that you maintain maximal force on the oar and that you adopt your normal rowing technique including your normal stroke length. Are there any questions?

Have you read and signed the informed consent sheet? Has your medical examination been completed and has the doctor cleared you to participate? Have you had your height, weight, date of birth and competition level recorded? Have your ECG electrodes been attached?

Please take your position on the ergometer and make any necessary stretcher adjustments (ECG monitor activated, doctor takes trace sample). Are you comfortable? If so, you can begin the 4 minute warm-up at the end of which you will have a brief period of time to collect yourself prior to the maximal effort.

Remember that you are free to withdraw from the test at any time and for any reason. If you feel unwell, are injured or you simply do not wish to continue, please feel free to stop.

If you are ready you may begin to warm-up.

**** 4 minute warm-up ****

That is the end of the warm-up period. How do you feel? Are you happy with the equipment? Are you ready for the maximal effort? If so, come half forward, are you ready? ROW !

# PHASE-ONE DEBRIEFING

The purpose of this study was to determine the relative importance of biomechanical performance variables derived from oar force and oar angle measures obtained during maximal ergometric rowing. Of particular importance were mean propulsive power output per kilogram of body weight, propulsive work consistency, stroke to stroke consistency and stroke smoothness.

This computer printout contains the results of your test. Apart from the data collected for the first 8 seconds of the test, each data line on page one represents 8 seconds (approximately 4 strokes) of data collected at each 30 seconds of the test. Sample data for each 30 seconds of the test includes stroke rate (/min), stroke length (degrees), peak force (newtons), work done (joules), propulsive work (joules), effectiveness (%), stroke-to-stroke consistency (%), and stroke smoothness (%). Mean scores for all variables are also indicated as are total scores for stroke rate, work done and propulsive work. The last two lines of data report your propulsive work consistency (%) and your mean propulsive power output per kilogram of body weight (watts/kg).

You are probably familiar with the variables stroke rate, stroke length and peak force (check!), however, I will briefly explain the nature of the other variables.

1. Work is the product of the torque applied to the oar handle and the oar angle.
2. Propulsive work is that portion of the work done in the direction of motion. Some of the total work done is dissipated in straining the side of the rowing ergometer (or boat) in a transverse direction.
3. Effectiveness describes the relationship between propulsive work and total work that is, that proportion of the work done used to propel the boat forward.
4. Stroke-to-stroke consistency is a measure of the accuracy with which the same force and angle values are traced from stroke-to-stroke.
5. Stroke smoothness is a measure of the level of co-ordination apparent in the application of force.
6. Propulsive work consistency is a measure of work capacity which represents the uniformity of the pattern of energy expenditure over the test effort. Page 3 of the test report contains a graph of your power output for the 6 minute maximal test. Peak force variation for the test duration is also graphed on page 3 of the test report.
7. Mean propulsive power output per kilogram represents rowing capacity and takes into account stroke length, force applied in the direction of motion and your body weight and is the average of the power output for the whole test.

Page 2 of the test report indicates the average shape and size of the force-angle profiles determined for each 8 second sample measured every 30 seconds of the test. The dotted line of the graphs indicates the standard deviation from the mean for the measured strokes. By examining the force-angle profiles you should be able to ascertain the effects of fatigue on such factors as peak force, peak force position, catch position, finish position and area under the curve which represents the work done. You should also be able to see a relationship between the size and shape of the various force-angle profiles and the pattern of power output outlined on page 3 of the test report.

Rowing requires high levels of consistency, coherence, accuracy and continuity. Once a rower's movement pattern has been established as being efficient, it needs to become as consistent as possible from stroke-to-stroke. Also, it has been suggested that the most physiologically effective method of energy expenditure is to reach mean power output as soon as possible and to maintain that level for the race distance. This strategy calls for a high level of propulsive work consistency which together with an increase in mean propulsive power output per kilogram of body weight should have a positive effect on average race velocity and therefore, final race time.

Are there any questions?

Thank you for your involvement in this study. I hope that the information you have obtained is of value to your rowing program. Please do not hesitate to contact me if you need any clarification regarding the information obtained or of the procedures used in this study.

## PHASE TWO PRETEST INSTRUCTIONS

Thank you for consenting to participate in this study. You will be required to complete a 6 minute maximal rowing ergometer effort at this test session and another in 7 days. Each test session will be preceded by a 4 minute warm-up. The warm-up should be submaximal, that is, about 70% oar force at 24 strokes per minute. Your electrocardiogram and heart rate will be monitored continuously during the tests. Data relating to stroke rate, stroke length, oar force and work done will be collected by a computer. This data will be available to you immediately following the second test. Are there any questions?

You should utilize your normal pattern of work output for a maximal rowing effort. Use your normal starting procedure and once you have completed the start phase you should maintain a stroke rate of around 33 strokes per minute. Do not allow your stroke rate to fall below 31 strokes per minute. I will call your stroke rate every 20 seconds and elapsed time every 30 seconds. It is important that you maintain maximal force on the oar and that you adopt your normal rowing technique including your normal stroke length. Are there any questions?

Have you read and signed the informed consent sheet? Have you had your height, weight, date of birth and competition level recorded? Has your medical examination been completed and has the doctor cleared you to participate? Have your ECG electrodes been attached?

Please take your position on the ergometer and make any necessary stretcher adjustments (ECG monitor activated, doctor takes trace sample). Are you comfortable? If so, you can begin the 4 minute warm-up at the end of which you will have a brief period of time to collect yourself prior to the maximal effort.

Remember that you are free to withdraw from the test at any time and for any reason. If you feel unwell, are injured or you simply do not wish to continue, please feel free to stop.

If you are ready you may begin to warm-up.

**** 4 minute warm-up ****

That is the end of the warm-up period. How do you feel? Are you happy with the equipment? Are you ready for the maximal effort? If so, come half forward, are you ready? ROW !

**APPENDIX F**

## PHASE TWO POSTTEST INSTRUCTIONS FOR THE CONTROL GROUP

Thank you for your involvement in this study and your willingness to undertake a second maximal rowing ergometer test in this 7 day period. This test will be exactly the same as the one you undertook seven days ago. The test will be preceded by a 4 minute warm-up. The warm-up should be submaximal, that is, about 70% oar force at 24 strokes per minute. Your electrocardiogram and heart rate will be monitored continuously during the tests. Data relating to stroke rate, stroke length, oar force and work done will be collected by a computer. This data will be available to you immediately following this test. Are there any questions?

Your total work output for the first test was _____ joules. Work is the product of the torque applied to the oar handle and the oar angle. Some of the work done is dissipated in straining the sides of the rowing ergometer (or boat) in a transverse direction. Therefore, there is a need to consider the work done in the direction of motion which is called propulsive work. Your propulsive work output for the first test was _____ joules.

By measuring the force applied to the oar handle during the stroke, I was able to produce a force-angle profile of your stroke. The average shape and size of the force-angle profiles determined for an 8 second period of each 30 seconds of your first test are plotted on this computer printout (indicate axes of graph, catch position, peak force position, force buildup and reduction, finish position, and recovery force on page 2 of the pretest report). If you examine the sequence of force-angle profiles you should be able to see the effects of fatigue on such factors as peak force, peak force position, catch position, finish position, and the area under the curve which represents the work done. The shape and size of the various force-angle profiles represents your pattern of work output for the 6 minute maximal effort (indicate differences in the size and shape of the force-angle profiles between the first, last, and the middle minutes of the pretest effort). This force-angle profile (indicate largest force-angle profile on page 2 of the pretest report) represents your best profile from the first test. This force-angle profile indicates a force of _____ newtons, a stroke angle of _____ degrees and represents a work output of _____ joules.

The purpose of this second test is to see if you can improve on your work output from the first test. You will need to achieve your best force-angle profile as often as you can. In order to do this, you will need to maximize force on the oar handle, aim for a higher peak force, increase the area under the curve and try to reduce any wasted movements at the catch and the finish. Are there any questions?

Please take your position on the ergometer and make any necessary stretcher adjustments (ECG monitor activated, doctor takes trace sample). Use your normal starting procedure and once you have completed the start phase you should maintain a stroke rate of around 33 strokes per minute. Do not allow your stroke rate to fall below 31 strokes per minute. I will call your stroke rate every 20 seconds and elapsed time every 30 seconds. Are you comfortable? If so, you can begin the 4 minute warm-up at the end of which you will have a brief period of time to collect yourself prior to the maximal effort.

Remember that you are free to withdraw from the test at any time and for any reason. If you feel unwell, are injured or you simply do not wish to continue, please feel free to stop.

If you are ready you may begin to warm-up.

**** 4 minute warm-up ****

That is the end of the warm-up period. How do you feel? Are you happy with the equipment? Are you ready for the maximal effort? If so, come half forward, are you ready? ROW !

## PHASE TWO POSTTEST INSTRUCTIONS FOR THE EXPERIMENTAL GROUP

Thank you for your involvement in this study and your willingness to undertake a second maximal rowing ergometer test in this 7 day period. This test will be exactly the same as the one you undertook seven days ago. The test will be preceded by a 4 minute warm-up. The warm-up should be submaximal, that is, about 70% oar force at 24 strokes per minute. Your electrocardiogram and heart rate will be monitored continuously during the tests. Data relating to stroke rate, stroke length, oar force and work done will be collected by a computer. This data will be available to you immediately following this test. Are there any questions?

Your total work output for the first test was _____ joules. Work is the product of the torque applied to the oar handle and the oar angle. Some of the work done is dissipated in straining the sides of the rowing ergometer (or boat) in a transverse direction. Therefore, there is a need to consider the work done in the direction of motion which is called propulsive work. Your propulsive work output for the first test was _____ joules.

By measuring the force applied to the oar handle during the stroke, I was able to produce a force-angle profile of your stroke. The average shape and size of the force-angle profiles determined for an 8 second period of each 30 seconds of your first test are plotted on this computer printout (indicate axes of graph, catch position, peak force position, force buildup and reduction, finish position, and recovery force on page 2 of the first test report). If you examine the sequence of force-angle profiles you should be able to see the effects of fatigue on such factors as peak force, peak force position, catch position, finish position, and the area under the curve which represents the work done. The shape and size of the various force-angle profiles represents your pattern of work output for the 6 minute maximal effort (indicate differences in the size and shape of the force-angle profiles between the first, last, and the middle minutes of the pretest effort). This force-angle profile (indicate largest force-angle profile on page 2 of the pretest report) represents your best profile from the first test. This force-angle profile indicates a force of _____ newtons, a stroke angle of _____ degrees and represents a work output of _____ joules.

The purpose of this second test is to see if you can improve on your work output from the first test. You will need to consistently reproduce a force-angle profile that is greater in magnitude than your average work ouput force-angle profile for the first test. To assist you in this task I have placed a template of your average work ouput force-angle profile for the first test on the oscilloscope screen

... / Cont.

directly in front of you. When you take a stroke you will receive immediate feedback on the extent to which that stroke matches the template. This feedback will be provided uninterrupted for the duration of the warm-up and maximal work phases. You will need to consider the force applied to the oar handle, force build-up, the magnitude of the peak force, the area under the curve and the presence of any wasted movements at the catch and the finish. Are there any questions?

Please take your position on the ergometer and make any necessary stretcher adjustments (ECG monitor activated, doctor takes trace sample). You may take some strokes to familiarize yourself with the feedback system. Can you see the trace clearly? Is the relationship between the trace and the template clear? Use your normal starting procedure and once you have completed the start phase you should maintain a stroke rate of around 33 strokes per minute. Do not allow your stroke rate to fall below 31 strokes per minute. I will call your stroke rate every 20 seconds and elapsed time every 30 seconds. Are you comfortable? If so, you can begin the 4 minute warm-up at the end of which you will have a brief period of time to collect yourself prior to the maximal effort.

Remember that you are free to withdraw from the test at any time and for any reason. If you feel unwell, are injured or you simply do not wish to continue, please feel free to stop. If you are ready you may begin to warm-up.

**** 4 minute warm-up ****

That is the end of the warm-up period. How do you feel? Are you happy with the equipment? Are you ready for the maximal effort? If so, come half forward, are you ready? ROW !

## PHASE TWO DEBRIEFING

These computer printouts contain the results of both your tests. Apart from the data collected for the first 8 seconds of each test, each data line on page one of both reports represents 8 seconds (approximately 4 strokes) of data collected at each 30 seconds of the test. Sample data for each 30 seconds of each test includes stroke rate (/min), stroke length (degrees), peak force (newtons), work done (joules), propulsive work (joules), effectiveness (%), stroke to stroke consistency (%), and stroke smoothness (%). Mean scores for all variables are also indicated as are total scores for stroke rate, work done and propulsive work. The last two lines of data on each printout report show your propulsive work consistency (%) and your mean propulsive power output per kilogram of body weight (watts/kg).

While you are familiar with the variables stroke rate, stroke length and peak force (check!), I will briefly explain the nature of the other variables measured during the two tests.

1. Work is the product of the torque applied to the oar handle and the oar angle.
2. Propulsive work is that portion of the work done in the direction of motion. Some of the total work done is dissipated in straining the side of the rowing ergometer (or boat) in a transverse direction.
3. Effectiveness describes the relationship between propulsive work and total work. That is, that proportion of the work done used to propel the boat forward.
4. Stroke-to-stroke consistency is a measure of the accuracy with which the same force and angle values are traced from stroke-to-stroke.
5. Stroke smoothness is a measure of the level of co-ordination apparent in the application of force.
6. Propulsive work consistency is a measure of work capacity which represents the uniformity of the pattern of energy expenditure over the test effort. Page 3 of the test report contains a graph of your power output for the 6 minute maximal test. Peak force variation for the test duration is also graphed on page 3 of the test report.
7. Mean propulsive power output per kilogram represents rowing capacity and takes into account stroke length, force applied in the direction of motion and your body weight and is the average of the power output for the whole test.

Page 2 of the test report indicates the average shape and size of the force-angle profiles determined for each 8 second sample measured every 30 seconds of the test. The dotted line on the graphs indicates the standard deviation from the mean for the measured strokes. By

... / Cont. over

examining the force-angle profiles you should be able to ascertain the effects of fatigue on such factors as peak force, peak force position, catch position, finish position and area under the curve which represents the work done. You should also be able to see a relationship between the size and shape of the various force-angle profiles and the pattern of power output outlined on page 3 of the test report. The force-angle profile on page 4 of the test report best reflects your average work output for the first test.

Rowing requires high levels of consistency, coherence, accuracy and continuity. Once a rower's movement pattern has been established as being efficient, it needs to become as consistent as possible from stroke-to-stroke. Also, it has been suggested that the most physiologically effective method of energy expenditure is to reach mean power output as soon as possible and to maintain that level for the race distance. This strategy calls for a high level of propulsive work consistency which together with an increase in mean propulsive power output per kilogram of body weight should have a positive effect on average race velocity and therefore, final race time.

The purpose of this study was to determine whether concurrent visual feedback of individual force-angle profile characteristics can be utilized to improve propulsive work consistency during maximal rowing and whether such improvement results in increased mean propulsive power output per kilogram of body mass. Following the first test you were randomly allocated to a control or experimental group. Immediately prior to the second test the rowers allocated to the control group were advised of the results of the first test and the strategies necessary to maximize work ouput via optimization of the force-angle profile. The rowers in the experimental group were provided with the same information but also received concurrent visual feedback of the force-angle profile which best represented the average pretest work output from the first test. This feedback took the form of a template of the force-angle profile which was placed on an oscilloscope screen in front of the rower. For every stroke, the rower was able to determine the extent to which the stroke matched the template. The feedback was provided uninterrupted for the duration of the warm-up and the maximal effort.

From a physiological perspective the achievement of the best possible result in rowing calls for the adoption of an even pace race strategy. A crew following such a strategy would begin the race with a moderately fast start, and then quickly settle into an optimal racing rhythm that is maintained throughout the race. No sprints would be attempted during the race and neither would the pace be increased towards the end with the traditional finishing kick. Ideally, the crew would achieve very similar intermediate 500 metre times. In order for the crew to perform in this manner, individual rowers would need to adopt a high level of propulsive work consistency.

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While even pace strategy is the preferred strategy for high level selection trials and when opposing clearly superior rivals, it is also a fact that in actual competition, the great majority of races are not rowed this way even at the elite level. This study sought to determine whether even pace strategy could be supported from a biomechanical perspective. As mentioned previously, the combination of a high level of propulsive work consistency and an increase in mean propulsive power output per kilogram of body weight should significantly influence average race velocity and therefore, final race time.

The data from this study indicates:

1. That club level male rowers are able to use concurrent visual feedback of individual force-angle profile characteristics to positively influence propulsive work consistency.
2. That club level male rowers who adopt higher levels of propulsive work consistency generate a significantly greater mean propulsive power output per kilogram of body mass.

Are there any questions? (Discuss rower's results).

Thank you for your involvement in this study. I hope that the information you have obtained is of value to your rowing program. Please do not hesitate to contact me if you need any clarification regarding the information obtained or of the procedures used in this study.

## APPENDIX I

### SAMPLE DATA FILE
### (PAGE 1 OF PRINTOUT)

Subject's name: AR

Date of birth: 12/7/60

Weight: 95.1kg

Time of test: 19:41:14.90

Date of test: 03/30/88

Height: 182cm

Comments: LEICHARDT GRADE 2

| SAMPLE NUMBER | SAMPLE START (sec) | STROKE RATE (/min) | STROKE LENGTH (deg) | PEAK FORCE (newt) | WORK DONE (joules) | PROP WORK (joules) | EFFECT IVENESS (%) | CONSIS TENCY (%) | SMOOTH NESS (%) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 40.5 | 72.5 | 959. | 14925. | 14288. | 95.7 | 70.8 | 83.6 |
| 2 | 30 | 36.1 | 76.1 | 1018. | 13755. | 13155. | 95.6 | 62.4 | 78.5 |
| 3 | 60 | 31.6 | 81.3 | 958. | 12090. | 11496. | 95.1 | 90.4 | 68.0 |
| 4 | 90 | 30.8 | 82.8 | 921. | 10755. | 10252. | 95.3 | 91.9 | 67.4 |
| 5 | 120 | 31.0 | 81.4 | 859. | 10505. | 10001. | 95.2 | 89.2 | 76.1 |
| 6 | 150 | 30.3 | 75.8 | 781. | 9146. | 8723. | 95.4 | 84.2 | 65.2 |
| 7 | 180 | 30.0 | 80.4 | 841. | 9137. | 8709. | 95.3 | 94.2 | 67.2 |
| 8 | 210 | 30.0 | 79.8 | 773. | 9155. | 8758. | 95.7 | 93.8 | 69.6 |
| 9 | 240 | 31.9 | 76.7 | 750. | 8914. | 8510. | 95.5 | 74.2 | 77.8 |
| 10 | 270 | 29.7 | 76.9 | 772. | 8243. | 7889. | 95.7 | 89.4 | 69.9 |
| 11 | 300 | 31.0 | 73.9 | 782. | 8250. | 7892. | 95.7 | 71.2 | 73.9 |
| 12 | 330 | 34.1 | 74.9 | 794. | 8752. | 8411. | 96.1 | 89.9 | 67.7 |
| 13 | 360 | 36.6 | 69.9 | 777. | 8829. | 8507. | 96.4 | 55.6 | 72.9 |
| TOTAL | | 391.2 | | | 122268. | 116853. | | | |
| MEAN | | 32.6 | 77.1 | 844.9 | 10189. | 9738. | 95.6 | 81.3 | 72.1 |

PROPULSIVE WORK CONSISTENCY = 82.2

PROPULSIVE POWER OUTPUT PER KILOGRAM = 3.41

# APPENDIX J

## PHASE ONE RAW DATA

| SUBJECT | ID | MPPO | SSC | PWC | SMO | GROUP |
|---|---|---|---|---|---|---|
| B.C. | 01 | 2.51 | 78.9 | 91.8 | 78.7 | 1 |
| P.C. | 02 | 2.82 | 74.4 | 92.1 | 74.7 | 1 |
| P.H. | 03 | 3.24 | 86.2 | 94.9 | 62.5 | 1 |
| D.K. | 04 | 2.86 | 90.0 | 94.1 | 67.2 | 1 |
| A.W. | 05 | 3.02 | 86.8 | 88.9 | 73.2 | 1 |
| M.K. | 06 | 2.73 | 76.9 | 80.8 | 72.3 | 1 |
| P.O'N. | 07 | 2.45 | 89.2 | 85.4 | 62.2 | 1 |
| R.W. | 08 | 3.59 | 89.9 | 96.6 | 69.4 | 1 |
| N.S. | 09 | 3.49 | 89.3 | 94.0 | 73.6 | 1 |
| P.G. | 10 | 4.01 | 93.2 | 92.4 | 69.2 | 2 |
| M.W. | 11 | 4.25 | 93.4 | 92.9 | 74.9 | 2 |
| C.W. | 12 | 3.54 | 91.7 | 86.3 | 71.5 | 2 |
| C.W. | 13 | 3.51 | 91.2 | 91.6 | 74.6 | 2 |
| R.L. | 14 | 4.21 | 93.1 | 94.3 | 70.6 | 2 |
| A.S. | 15 | 3.42 | 92.4 | 95.0 | 79.6 | 2 |
| A.M. | 16 | 3.60 | 93.0 | 93.3 | 72.7 | 2 |
| T.W. | 17 | 3.57 | 91.4 | 92.0 | 70.1 | 2 |
| A.B. | 18 | 4.32 | 94.8 | 93.8 | 72.4 | 2 |
| P.W. | 19 | 2.81 | 89.8 | 94.3 | 69.9 | 2 |
| I.C. | 20 | 3.67 | 90.3 | 93.4 | 75.7 | 2 |
| P.M. | 21 | 3.17 | 92.5 | 91.7 | 71.5 | 2 |
| P.C. | 22 | 3.97 | 92.2 | 87.2 | 68.7 | 2 |
| K.M. | 23 | 4.03 | 91.5 | 96.0 | 79.9 | 2 |
| K.R. | 24 | 3.60 | 93.4 | 96.4 | 69.8 | 2 |
| S.I. | 25 | 4.05 | 93.3 | 90.6 | 75.3 | 2 |
| W.A. | 26 | 4.28 | 93.7 | 97.2 | 78.6 | 2 |
| J.C. | 27 | 3.46 | 92.6 | 91.3 | 68.7 | 2 |
| S.B. | 28 | 3.59 | 90.3 | 94.4 | 68.9 | 2 |
| S.D-J. | 29 | 3.29 | 86.1 | 94.0 | 69.6 | 2 |
| G.M. | 30 | 3.74 | 92.8 | 92.3 | 73.1 | 2 |
| S.S. | 31 | 3.01 | 90.7 | 95.2 | 70.6 | 2 |
| M.W. | 32 | 2.81 | 89.8 | 94.3 | 69.9 | 2 |
| B.D. | 33 | 4.75 | 93.0 | 96.0 | 74.0 | 3 |
| L.H. | 34 | 4.52 | 94.0 | 97.0 | 73.0 | 3 |
| D.M. | 35 | 4.99 | 94.0 | 95.0 | 73.0 | 3 |
| N.H. | 36 | 4.40 | 94.0 | 90.0 | 76.0 | 3 |
| A.R. | 37 | 4.64 | 93.0 | 93.0 | 74.0 | 3 |
| M.H. | 38 | 4.74 | 94.0 | 94.0 | 77.0 | 3 |
| A.Mc. | 39 | 4.50 | 92.0 | 93.0 | 67.0 | 3 |
| T.S. | 40 | 4.47 | 92.0 | 94.0 | 72.0 | 3 |
| B.H. | 41 | 4.46 | 94.0 | 92.0 | 77.0 | 3 |

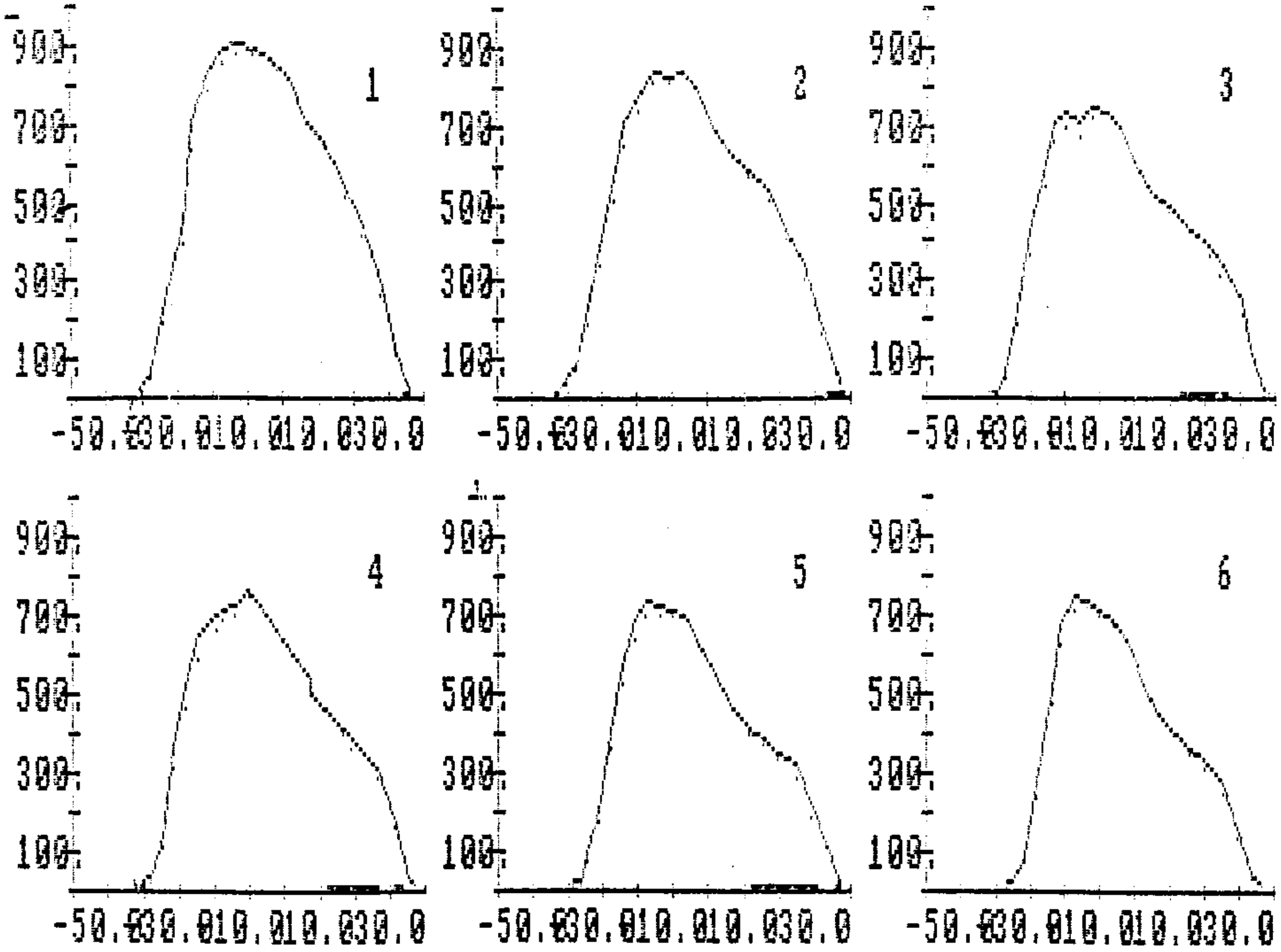
1 = Novice rowers, 2 = State level rowers, 3 = National level rowers

## PHASE TWO RAW DATA

| SUBJECT | ID | PRETEST PWC | POSTTEST PWC | PRETEST MPPO | POSTTEST MPPO | GROUP |
|---|---|---|---|---|---|---|
| C.O'H. | 01 | 95.9 | 94.5 | 3.31 | 3.78 | 1 |
| T.B. | 02 | 95.0 | 94.8 | 3.88 | 4.11 | 1 |
| A.W. | 03 | 83.2 | 94.8 | 3.61 | 4.14 | 1 |
| J.C. | 04 | 91.6 | 89.8 | 3.72 | 3.74 | 1 |
| P.G. | 05 | 88.3 | 82.6 | 3.69 | 3.41 | 1 |
| A.F. | 06 | 91.0 | 91.5 | 3.99 | 3.93 | 1 |
| P.C. | 07 | 90.5 | 97.6 | 3.59 | 3.55 | 1 |
| A.Mc. | 08 | 90.7 | 96.3 | 3.77 | 3.75 | 1 |
| A.J. | 09 | 90.4 | 92.7 | 3.84 | 3.77 | 1 |
| P.S. | 10 | 91.8 | 94.5 | 4.28 | 4.47 | 1 |
| C.M. | 11 | 84.6 | 88.6 | 3.84 | 4.01 | 1 |
| R.M. | 12 | 84.4 | 83.0 | 3.22 | 3.56 | 1 |
| A.R. | 13 | 82.2 | 85.6 | 3.41 | 3.40 | 1 |
| A.P. | 14 | 95.9 | 95.8 | 3.83 | 3.99 | 1 |
| M.R. | 15 | 75.1 | 91.9 | 2.77 | 2.69 | 1 |
| C.Mu. | 16 | 82.6 | 91.5 | 3.03 | 3.32 | 1 |
| H.B. | 17 | 83.6 | 95.7 | 3.65 | 3.65 | 1 |
| M.H. | 18 | 94.1 | 90.3 | 4.28 | 4.30 | 2 |
| R.H. | 19 | 94.3 | 93.7 | 3.88 | 3.97 | 2 |
| B.T. | 20 | 96.1 | 92.4 | 4.07 | 4.00 | 2 |
| N.L. | 21 | 86.8 | 86.7 | 3.38 | 3.66 | 2 |
| P.S. | 22 | 90.7 | 91.3 | 3.29 | 3.60 | 2 |
| S.C. | 23 | 91.3 | 89.5 | 3.82 | 3.92 | 2 |
| G.M. | 24 | 89.6 | 84.3 | 3.98 | 3.76 | 2 |
| A.S. | 25 | 86.0 | 85.7 | 3.30 | 3.34 | 2 |
| O.W. | 26 | 96.3 | 90.2 | 4.20 | 4.35 | 2 |
| P.T. | 27 | 71.9 | 75.8 | 3.38 | 3.09 | 2 |
| R.T. | 28 | 73.2 | 66.8 | 3.27 | 2.37 | 2 |
| M.K. | 29 | 90.8 | 83.3 | 2.93 | 2.89 | 2 |
| P.O. | 30 | 95.2 | 92.7 | 2.89 | 2.68 | 2 |
| A.W. | 31 | 95.2 | 77.2 | 2.94 | 2.95 | 2 |
| D.K. | 32 | 94.1 | 92.4 | 2.86 | 2.01 | 2 |
| P.C. | 33 | 87.7 | 94.2 | 2.80 | 2.81 | 2 |
| D.Mc. | 34 | 90.0 | 94.0 | 3.13 | 3.32 | 2 |

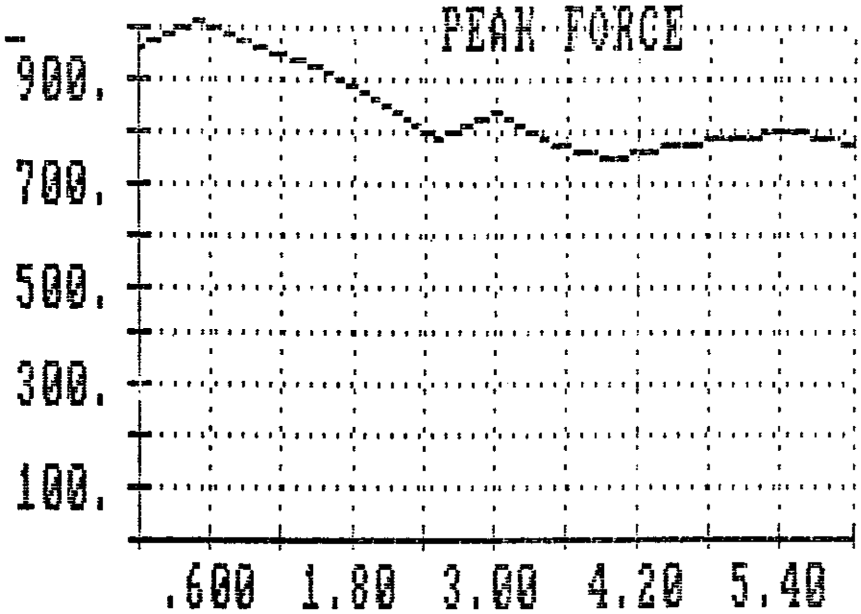
1 = Experimental group, 2 = Control group

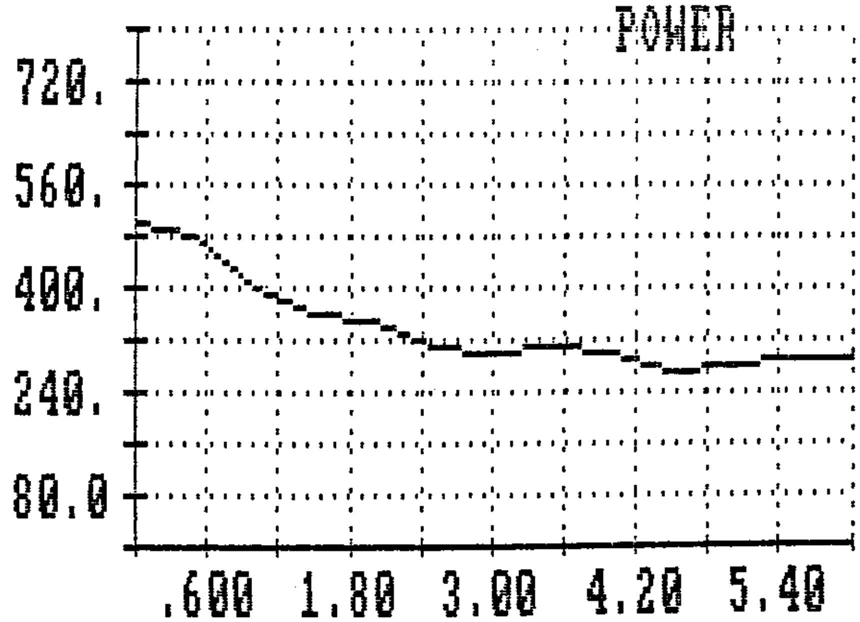
## APPENDIX I (CONT.)



SAMPLE DATA FILE
(PAGE 2 OF PRINTOUT)

## SAMPLE DATA FILE
## (PAGE 3 OF PRINTOUT)





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