Dynamics of coordination within elite rowing crews: evidence from force pattern analysis

HOLGER HILL*

Faculty of Biology, University of Marburg and Institut für Grenzgebiete der Psychologie und Psychohygiene, Freiburg, Germany

Accepted 3 August 2001

For a rowing crew to be successful, the movements of the rowers need to be well coordinated. Because rowers show individual force patterns, they have to adapt their movements when rowing as a crew. In this exploratory study, these hypothesized changes in movement pattern were examined. The force graphs of six elite coxless fours crews were recorded over 11 training runs using strain gauges attached to the oars. A detailed force analysis showed that form differences, but not area differences, between force patterns decreased when force output increased as a result of two different processes. First, increasing force output reduced form differences instantaneously by reducing the individual variation in force patterns. Secondly, the kinaesthetic perception of form differences is easier than that of area differences. This better perception facilitates the adaptation of movement patterns, especially when force output is high.

Keywords: biomechanics, coordination, force, motor control, rowing, rowing crews.

Introduction

As every experienced rower and coach knows, rowing in a crew is much more efficient when the coordination between crew members is high - that is, they have similar movement patterns (Atkinson, 1896; Ishiko, 1971; Samsonov et al., 1975; Schneider et al., 1978). Efficient rowing will result in the highest boat speed for a given power output. Thus the crew members will view the boat as running well, independently of the class of the boat. According to Williams (1967), poor synchronization of movement patterns among a crew will adversely affect the coordination of movement of crew members and cause additional movement of the boat, including yawing, rolling and pitching. These adverse effects include a reduced power output and a waste of effort because of increased friction. In contrast, the friction caused by the oscillation of the shell during the rowing cycle can only be marginally controlled by the rowers. This oscillation is a physical constraint of the intermittent propulsion of a rowing shell, which increases with stroke rate (Hill, 1997).

Elite rowers are better able to synchronize the kinematics of their movements. The dynamic features, however – especially the force pattern – are more dif-

ficult to synchronize because individual rowers develop their own force pattern during practice. This was first reported by Atkinson (1896, 1898) and subsequently noted by several authors (Ishiko, 1968, 1971; Nolte, 1981; Ishiko *et al.*, 1983). In 1963, Ishiko (1968) even found differences in force patterns within the worldleading eights crews of Ratzeburg and Vesper Boat Club. In contrast, successful rowers show similar force patterns when they have been rowing together for a long time. Haenyes (1984) studied four groups of rowers who had rowed together for at least 2 years under the same coaches. He found similar force patterns within groups but different ones between groups (Fig. 1). Schneider *et al.* (1978) reported similar results.

Evidence for adaptation of force patterns when oarsmen have been rowing together for a long time comes from the coxed and coxless pairs (Adam *et al.*, 1977; Koerner and Schwanitz, 1985). Because of the positions of the oars relative to the boat, in the coxed and coxless pairs different force patterns are required of the stroke and bowman to keep the boat moving in a straight line. If this requirement is not met, the power output of the rowers will be channelled into yawing the boat, while the detour of the shell will be neglectably small (Hill, 1997). Therefore, the force pattern of the stroke has to be steeper after the catch and has to peak earlier, whereas that of the bowman has to peak later and to fall more quickly towards the finish. Such adaptation to the

^{*} Address all correspondence to Holger Hill, Fichtestr. 30, D-69126 Heidelberg, Germany. e-mail: holger.hill@urz.uni-heidelberg.de



Fig. 1. Typical force–time curves of four different training groups: (1) Essen, (2) Osnabrück, (3) Dortmund, (4) Hannover. A = catch, O = perpendicular position of the oar, E = finish. Reproduced with permission from Haenyes (1984).

specific requirements of a particular class of boat requires considerable physiological adaptation. Roth *et al.* (1987, 1993) studied coxed and coxless pairs and found higher metabolic rates (lactic acid, oxygen uptake, heart rate) in strokes than bowmen in early peaking force patterns compared with mid-peaking force patterns, although their power output was similar.

Most biomechanical studies of rowing have only analysed selected force-time curves using qualitative methods (i.e. plotting and visual inspection). Using such methods, a few researchers have described changes in force patterns. For example, Schneider *et al.* (1978) studied a coxless fours who had been advised to row with special care in the first part of the stroke during long-distance training and found changes in the force patterns of two of the four rowers. Hill (1986) examined the synchronization of force profiles in the first minutes at the beginning of a training session in a double sculls crew who were rowing for the first time in 2 months after a break from rowing together. After changing the rowers' seat positions, their force patterns showed desynchronization that decreased with time.

Few studies have analysed longer time-series of force-time curves. In investigating the multiple factors

that contribute to rowing performance, Schneider (1980) measured the force patterns and angles of the oar of 12 coxless pairs over 2000 m to compute stroke power. Mattes (1999), in collaboration with the FES – an institution founded in the former East Germany to support elite athletes with high-tech material and biomechanical diagnostics (Altenburg *et al.*, 1996) – measured force-time curves, rowing angle, force applied to the stretcher, velocity and acceleration of the shell in four eights during selection for the Junior World Championships. Stroke power and rowing angle at the catch and finish positions were analysed. The variation in rowing angle was limited, whereas stroke power varied during races, independent of the absolute power and racing success of the crew.

Wing and Woodburn (1995) analysed the force patterns of four elite rowers seated in the bow of an eights shell for 22 min. By calculating the mean and standard deviation of 30 consecutive force graphs of each of the four rowers, they were able to assess the stability and variability of individual force patterns. Individual force remained consistent and the small interindividual differences were maintained, independently of the change in seat positions of two of the rowers.

In a complex analysis of movement, Lippens (1992a) combined psychological ratings to assess the 'subjective theories' of rowers about their movement behaviour with biomechanical measures. He assessed motor learning and motor control in novice (Lippens, 1992b) and elite rowers. In an elite women's coxless pair, he showed that the stroke varied her movement pattern significantly more than the rower in the bow to control the movements of the shell (Lippens, 1999).

Each rower has his or her own individual force pattern. In contrast, crews who have rowed together for a long time adapt their force patterns, dependent on the specific requirements of the class of the boat – similar force patterns in shells with a symmetrical rig (double sculls, quadruple sculls and, with some constraints, the eights and fours) and asymmetrical force patterns in the coxed and coxless pairs. Adaptation, therefore, occurs over time when rowers are combined in crews. The aims of the present study were to develop a method to analyse the stability and variability of individual movement patterns and within-crew coordination, and to apply this method in an exploratory field setting to examine adaptation in force patterns.

Methods

Participants and procedure

The participants were 20 oarsmen from the former 'Lightweight Project' (Fritsch, 1988; Galster and Fritsch, 1988), a group of elite rowers from whom the members of the German national rowing squad (oared boats and quadruple sculls and, occasionally, all lightweight boat classes) were selected for several years. The physical characteristics of the 20 participants were as follows: age 22–31 years, height 1.75–1.90 m, body mass 70–78 kg.

Testing was carried out at two training camps on the Rhein-Main-Donau channel at Erlangen and at the Olympic racing course in Munich. One aim of these camps was to adapt individual rowing techniques; combinations of crew members, therefore, were often changed. The 20 oarsmen rowed either in one of three coxless fours or an eight. Only one of the coxless fours was measured each training run. Seven training runs were recorded at training camp 1 and four runs at training camp 2. The training runs, which lasted 60-100 min, were recorded for 45-90 min. The content of the training runs was different: endurance, technique sections, intensive sections up to racing pace. Identical combinations of crew members were assessed one to five times. The force patterns of 16 of the oarsmen were recorded one to six times.

The outriggers were attached on alternate sides. Stroke position was starboard during training camp 1 and portside during training camp 2. Therefore, to row on their favoured side, the oarsmen did not always sit in their preferred position. Additional analysis was made of a coxless pair and an eight at a training camp that preceded the World Championships. All boats used were K-series racing shells (Empacher, Eberbach, Germany).

Data recording

As in previous studies (Schneider, 1980; B. Haenyes and K.P. Troch, unpublished results), force patterns were recorded using four strain gauges (HBM, Darmstadt, Germany) glued on to macon-bladed carbon oars (Concept 2, Morrisville, VT, USA) inboard near the point of rotation, after consultation with the HBM engineer's office in Giessen. The strain gauges were wired into a Wheatstone bridge. After amplification with purpose-built amplifiers and voltage-tofrequency conversion, the data were stored on tape using a modified four-channel Sony-Walkman. Using a 90 min tape, 45 min of rowing data could be stored. Attaching the measurement system to the shell took only a few minutes. The rowers had only to attach the cable to their oar, switch on the power button, start the tape-recorder and, if necessary, change the tape. The mass of the whole measuring system, including the four cables, was 2.1 kg. For the additional measurement of rowing angle in a single scull and a coxless pair, potentiometers (Dinpoint P2501, Novotechnik, Ostfildern, Germany) were mounted on the oar gate.

For offline analysis, the data were reconverted from frequency-to-voltage and digitized using 12-bit resolution at a sampling rate of 100 Hz. The data storage system used in the boat was tested in the laboratory by simultaneously recording the force patterns using this system and a computer.

For calibration, the oars were fixed with the outer edge of the blade propped up under the oarlock. The edge of the blade and the long axis of the oar were orientated in the horizontal plane. Dumb-bell discs were attached 15 cm from the ends of the handle. The data were stored on tape as described above. Calibration was performed before and after the training camps. No differences between calibration measures were observed. To obtain the calibration factors, the difference between two loads was calculated. Initially, the oars prepared for force measurement were tested successfully for linearity and non-hysteresis both statically by adding and replacing discs and dynamically using an ergometer force transducer.

The oars were 3.84 m long; the length of the inboard part of the oar was 1.14 m in the eight, 1.15 m in the coxless four and 1.16 m in the coxless pair.

Force analysis

Software written by the author detected single forcetime profiles automatically and discarded strokes contaminated by artefacts. Using a five-step moving average algorithm, the data were smoothed; this smoothing was comparable with using a 20 Hz low-pass filter. Because of offset drifts during recording, each force pattern was adjusted to a baseline. This was computed from a 240 ms epoch in the middle of the recovery phase that preceded the current stroke. In this part of the recovery phase, the oar moves with nearly constant horizontal velocity, with the positive and negative vertical and horizontal acceleration forces applied to the oar neutralizing one another. The data from this baseline correction were saved into a file and controlled manually. At higher stroke rates, with a shortened recovery phase and increasing acceleration applied to the oar, this algorithm did not always work properly. In such cases, the baseline was corrected manually, with an offset derived from visual inspection of the data.

To discard the forces produced by the changes in the direction of movement of the oar around the catch and finish and forces produced by possible effects of drag, the steepest slopes of beginning (below a threshold of 50% of the peak force) and end (below a 30% threshold) of force graphs were calculated and tangents fitted that were extrapolated to the baseline (Fig. 2a). Negative values of the force pattern (below baseline)



Fig. 2. Method of force pattern analysis (see text for details). (a) Extrapolation and clipping of catch and finish. (b) Computation of smoothness. The shaded difference area related to the force pattern area provides the value for smoothness, in this case 4%. (c) Centre of force pattern. The dotted vertical line splits the force pattern into two halves of equal area. The position of the vertical line on the time axis, related to stroke duration, provides the value for the centre, in this case 45.8%. Stroke duration is set to 100%. (d) Computation of differences between force patterns. The shaded difference area related to the force pattern area provides the difference area related to the force pattern area provides the difference value, in this case 13.9%.

were removed. This approach was used to allow an examination of within-crew coordination during the drive phase. A separate analysis of the forces produced by the effects of drag and acceleration of the oar was not performed. The onset and end of the force pattern was calculated following the method of Schneider (1980), the validity of which was confirmed by high-frequency filming of the contact of the blade with the water. The use of thresholds is necessary when the force patterns of novice rowers are analysed (Hill, 1995; Hill *et al.*, 1995), because these patterns generally are not as smooth as those of elite rowers, with the steepest slopes at the catch and finish. Because the software was used to analyse the data of both groups of rowers, the threshold function was implemented.

From single force-time curves for each stroke, several variables were computed. The variables for which results are reported are listed below. Variables from single force graphs are numbered from 1 (stern or stroke position) to 4 (bow) according to seating position.

- *Duration of drive phase* (s): end time onset time of force-time curve.
- *Stroke rate* (min⁻¹): 60/(onset time of stroke onset time of previous stroke).
- Area under the force curve (N·m·s): this provides information about the propulsive force production of a rower similar to the power production (integral of the force-time curve × rowing angular velocity) because angular velocity depends on area. If the area

is increased by maintaining the stroke rate, the shell will be propelled faster through the water and angle and movement velocity will also increase (Hill, 1995). Some authors have computed peak force only; however, this variable is unsuitable because force patterns can vary, especially in novice rowers, and they can look markedly different between elite rowers (from almost rectangular to triangular).

- Smoothness of force (%): to compute smoothness, a line was drawn over the concave segments of the force pattern as shown in Fig. 2b. The algorithm checked for maxima and turning points and computed the area between the force pattern and the interpolated line between two maxima or turning points. This area was related to that of the force graph. In the case of multiple maxima or turning points, the largest possible area was computed; for example, if a graph contained three maxima, the line was generated between the first and third maximum if the second maximum did not cut the line. If the second maximum did cut the line, two separate lines were generated from the first to the second maximum and from the second to the third maximum. I assume that the smaller the smoothness factor, the better the movement pattern (in a semi-quantitative way, because it is not known exactly how smoothness and efficiency of movement are related).
- *The centre of the force graph* (%): this was computed to determine whether the force patterns could be assigned to a harder catch, a harder finish or a pattern somewhere in between. The point at which the force

graph was divided into two halves of equal area was computed and related to the duration of the drive phase (Fig. 2c).

For the analysis of within-crew variation in force patterns, the differences between individual graphs were computed. These differences were divided into area differences (used to estimate the applied power) and form differences (used to estimate the movement pattern). These differences were related to the mean area for two reasons. First, the efficiency of a crew and the related differences in force pattern are important when force output is high, as in competition. In contrast, a waste of energy is less important when rowing well below maximum power output. Additionally, it has been hypothesized that the perception of differences is improved when force output is high. Secondly, the aim of reducing differences is to achieve congruency. When two strokes with different force outputs - but with the same absolute difference to the reference curve - are compared, the congruency will be higher when force output is high.

The following variables were computed:

- *Synchronization of the onset and finish of a stroke* (ms): time differences (onset and finish) between the force pattern of the stroke of a rower and those of the other rowers.
- Area difference (AreaDiff) (%): the mean area was computed initially (average of the areas for each stroke). Then, the differences between the individual areas and the mean area were calculated. The absolute values of the individual area differences were averaged to the mean area difference (MeanAreaDiff) (N ⋅ m ⋅ s). Mean and individual area differences were related to the mean area (AreaDiff×100/mean area).
- Total difference (TotalDiff) (%): the force patterns of each stroke were averaged over time (sample by sample) to a common force pattern of the crew. From this common force pattern, the individual force patterns were subtracted and the areas of these differences (as absolute values) related to the area of the common curve. Individual differences were averaged to the mean total difference (MeanTotalDiff) (Fig. 2d).
- Form differences (FormDiff) (%): this variable was calculated similarly to the total difference. To exclude differences in areas (i.e. to compute only the differences in the shapes of the force-time curves), all force patterns (of the current stroke) were normalized to the same area before computing differences.

To adapt an individual force pattern to a common crew style, a rower can use two types of kinaesthetic information: his own force production and his own movement velocity (measured as the angular velocity of the joints and the velocity of muscle contraction). If the propulsive power is increased, the speed of the shell and, therefore, movement speed will also increase. With some constraints (e.g. slip of the blade, rowing angle, class of boat), the speed of the shell depends on the propulsive force output of all rowers. Therefore, the common force pattern was taken as the reference.

Descriptive and statistical analysis

Because of the exploratory and non-standardized design of this study, the statistical analysis was restricted. Three methods were used to analyse the data: (1) descriptive analysis of time series, (2) correlation analysis of time series and (3) analysis of mean values with parametric and non-parametric statistical methods.

For the descriptive analysis, the results were plotted as a time series and analysed by visual inspection in a comparison of different variables and different times of measurement. For presentation purposes, the results plotted as a time series were smoothed using a five-step moving average algorithm.

For the statistical analysis, the contents of the training runs, which were carried out to develop the different physiological and coordination skills necessary for competitive rowing, were protocolled. Sections of intensive rowing, from 10 strokes to 100 strokes in 3 min, were performed at or just below race speed in nine of the 11 training runs. The different parts of a training run (endurance, intensive) were identified from stroke rate and mean area. Mean values and standard deviations of the different variables from the force patterns were computed separately according to intervals of intensive and endurance rowing. Only those strokes assigned without hesitancy to these intervals were included in the mean calculation; that is, relaxation strokes immediately after an interval at race pace were excluded from the mean calculation of the following endurance interval. The correlation analysis of time series was performed on these mean values of the different intervals. Additionally, for case studies, correlation analysis was applied to the single stroke data.

Since the number of measures differed between rowers, the mean values entered into analyses of variance were computed as follows: First, the mean values of the different intervals were averaged for each training run and rower, separately for intensive and endurance sections. Secondly, for rowers measured more than once, these averages were collapsed across training runs. So, for the computation of smoothness and the synchronization of the catch and finish, only two values (endurance and intensive) were entered for each rower in the analysis of variance (ANOVA). To assess the influence of seating position on the centre of force patterns, mean values were calculated separately for each rower and for each position. For example, rower K was measured in training run V534 in the bow position and in runs V55 and V56 at position 3; in this case, the mean value for V534 was compared with the average of the mean values of V55 and V56 (see Table 1).

Interactive variables, which depend on the combination of crew members, were analysed as a crew average (e.g. form differences, area differences, duration of drive phase). Variables that are predominantly influenced by individual factors were calculated separately for each rower (e.g. smoothness and centre of force patterns, synchronization of catch and finish).

Results

The results from 11 training runs in the coxless fours were recorded. One crew was assessed five times (V44, V534, V55, V56, V58); the other six recordings were for different combinations of crew members (V45, V467, V489, V50, V512, V57), of whom there were 14. There were some technical problems. In V44, for example, only the first 15 min could be recorded and in V58 only three of the four force patterns were recorded. Also, in V50, force patterns could not be calibrated because the oars were attached to the wrong amplifiers. In two training runs (V489 and V50), one of the coaches took the place of a rower. An overview of the 11 training runs, the different combinations of crew members and crew averaged variables is given in Table 1.

Smoothness of force graphs

In general, smoothness scores varied between rowers and could also vary in a single rower in the same training run or between training runs. Greater variability in the time course of the smoothness score within training

Table 1. Mean values for stroke rate (min^{-1}) , mean area $(N \cdot m \cdot s)$, duration of the drive phase (ms), form differences (%) and area differences (%) calculated separately for the different contents and intensities of training run

Run	Crew	Intensity	Stroke rate	Mean area	Duration	Form differences	Area differences
V44	DFGK	Е	24.2	232	815	8.0	4.7
V45	EFDM	Е	24.5	231	799	9.0	11.3
		Ι	40.7	256	649	6.3	9.2
		К	13.5	291	850	8.9	10.3
V467	HLNA	Е	24.6	244	816	11.7	7.1
		Ι	31.6	269	735	8.0	9.1
V489	NABJ	Е	23.4	241	806	13.7	8.9
V50	NMPJ	Е	25.0	N.A.	765	9.9	N.A.
		Ι	32.7	N.A.	696	9.6	N.A.
V512	HLEC	Е	24.8	249	789	7.3	5.5
		Ι	38.1	296	705	5.0	4.5
V534	DFGK	Е	24.2	217	782	10.2	5.5
		Ι	35.3	255	698	7.9	3.7
V55	FDKG	Е	23.4	225	809	9.6	8.2
		Ι	32.6	246	712	7.0	5.7
		K	13.1	300	901	8.5	6.8
V56	FDKG	Е	25.1	209	782	10.2	6.5
		Ι	33.6	234	703	7.5	8.6
V57	OIMP	Е	23.9	225	764	11.4	9.5
		Ι	34.3	234	687	9.9	8.1
V58	FDKG	Е	24.6	229	777	9.7	7.7

Note: Based on the averages of all four oarsmen over 11 training runs. E = endurance intervals, I = intensive intervals, K = intervals with high force output but very low stroke rates. The duration of the (single) intensive intervals was 10–30 strokes, except in V467 and V534, where it was 70–100 strokes. Each of the 16 oarsmen is identified by a letter (A–P). For the different combinations of crew, the oarsmen are listed according to their seating position from stern to bow (e.g. the crews in training runs V534 and V55/56 were made up of the same rowers sitting in different positions). N.A. = not available.

107

runs than between training runs (for the oarsmen who had more than one training run recorded) indicated no improvement during the training camps. With a few exceptions, the smoothness in the intensive training sections was better than, or at least equal to, that in the endurance sections with the smoothest curves. High scores indicating a lack of smoothness were seen immediately after the intensive sections (Fig. 3a,b). Statistical analysis confirmed the results of the visual inspection.

To compare smoothness for intensive and endurance rowing, the mean scores were calculated for each rower across intervals and across training runs (periods of relaxation were not included). Smoothness was found to be better during intensive (mean 1.16%) than during endurance (mean 1.56%) rowing. A one-way ANOVA with smoothness as the dependent variable and intensity as a repeated-measures factor revealed a statistical trend for this difference ($F_{1,14} = 3$, P < 0.1). Any improvement in smoothness during the training camps was assessed using the data of 10 oarsmen, who had at least two training runs recorded that contained sections of intensive training. A two-way multivariate analysis of variance (MANOVA), with intensity and time (first and last measured training run) as repeatedmeasures factors revealed no significant main effects or a time \times intensity interaction.

Synchronization of catch and finish

Visual inspection showed that time differences for the beginning and end of the force patterns of the crew members in relation to the rower in stroke position were generally lower for the catch than for the finish. In the endurance sections, the differences were generally greater than in the intensive sections. The highest values were recorded in periods of relaxation. A systematic reduction in these differences during the course of training runs or the course of training camps was not observed. A two-way MANOVA (endurance *vs* intensive



Fig. 3. (a) Time course of smoothness of the force pattern of rower 2 (upper trace) in training run V467 and stroke rate (bottom trace). Smoothness is better when intensity, as indicated by higher stroke rates, is high. During relaxation periods immediately after the intensive rowing intervals, smoothness is at its worst. The arrows indicate the rowing strokes from which the force patterns in (b) are drawn. (b) Force patterns of rower 2 during endurance rowing (upper trace; arrow u in (a)) and during intensive rowing (bottom trace; arrow b in (a)).

and catch vs finish) revealed significant main effects for intensity ($F_{1,12} = 5.53$, P = 0.037) and for catch versus finish ($F_{1,12} = 25.9$, P < 0.001). The mean values for the synchronization of the catch were 14.2 ms for endurance and 11.2 ms for intensive; for the synchronization of the finish, these values were 25.8 and 21.7 ms respectively.

Centre of force patterns

A clearly visible and larger variability of the centre score time course within training runs than between training runs (for those oarsmen who had more than one training run recorded) indicated no systematic change during the training camps and no dependence on seating position. Mean centre scores (computed analogously to the smoothness scores) revealed a significant difference ($F_{1,14} = 5.74$, P = 0.031) between the endurance (mean 44.8%) and the intensive (mean 45.4%) sections. For a coxless four with an asymmetric rig (outriggers fixed alternately), one would expect an asymmetric force pattern comparable to that of a coxless pair, but not so defined because of the larger boat. However, three rowers with considerably higher centre scores (range 48-50%) than the other oarsmen retained these high scores when changing from the bow position to another position in the boat.

Two one-way repeated-measures analyses of variance were performed on the data of eight (nine for endurance rowing only) rowers who were assessed at least twice in different seating positions. Because of insufficient data, not all four seating positions could be compared. Therefore, the mean centre scores for these eight (nine for endurance rowing only) rowers were calculated across training runs but differentiated according to whether the seating position was towards the stern or towards the bow. As expected, a two-way MANOVA found no statistically significant difference. Mean values for endurance rowing (n = 9) were 46.2% for the stern and 45.6% for the bow; for intensive rowing (n = 8), these figures were 46.0% and 45.9% respectively.

In contrast to the coxless fours, a systematic change in the centre of force pattern was seen in a coxless pair, who rowed first in the pair and then a few hours later in the eight. The typical asymmetric pattern for a good coxless pair, with an earlier centre of force pattern for the rower in the stroke position, was noted. This asymmetric pattern was maintained for the first 40 rowing cycles in the eight, but then disappeared as is required for successful rowing in an eight (Fig. 4).

Differences in force patterns: case studies

Case 1. Figure 5a shows the time course of the total difference and of the form difference (crew average) for

the first 45 min of training run V57. Both of these differences were reduced during the first 150 strokes. The greatest differences (around strokes 160, 340 and 530) were found after turning the boat and beginning rowing in the opposite direction of the 2000 m course. The smallest differences were found during sections of intensive rowing (30 strokes at race pace). Analysis of individual data revealed that the large differences at the beginning of the training run and the subsequent decrease were caused by the bowman (Fig. 5b). The individual form difference of his force graph was greater than the mean form difference (crew average) for the first 80 strokes. He reduced his form difference by improving the smoothness of his force pattern and synchronization of the catch and by shifting the centre of his force patterns from the catch towards the middle of the stroke (Fig. 5b). Typical force patterns for large (strokes 25-27) and small (strokes 244-246) differences in endurance rowing and for intensive rowing (strokes 696–698) are shown in Fig. 5c.

Case 2. In contrast to V57, the crew in training run V512 showed no systematic reduction in differences over 90 min (Fig. 6). The smallest differences in force patterns were found during intervals at race pace; the largest differences were found during relaxation immediately after such intervals. Between strokes 1200 and 1400, the total difference was greatest because of an increase in area differences; form differences remained low. This crew recorded the smallest differences between force patterns and was unbeaten in test races and competition. The data for this crew were recorded from its sixth common training run (the fourteenth run overall). It is unclear, therefore, whether the good coordination of this crew was unique or the result of its five preceding training runs.

One crew performed its fifth successive training run in V44, but did not show the same coordination as the crew in V512. Moreover, the crew in V57 performed several common training runs before, but these were interspersed with rowing in an eight or in different combinations of rowers in the fours.

The data for the crews in the above two case studies represent extremes in differences in force patterns. A similar but less pronounced pattern as that seen for the crew in V57, with a reduction in total differences and form differences at the beginning of the run and maintenance of these differences, was seen in two other crews (training runs V45 and V55/56). Some of the other crews showed a reduction in differences in force patterns over time in parts of longer sections of intensive rowing or in medium-intensity rowing. In general, an intensity reduction or relaxation saw differences increase (Fig. 7). Form differences and area differences were not related. In some cases, both variables showed



Fig. 4. (a) Time course of changes in the centre of force patterns of two rowers dependent on the requirements of different boat classes. The last 100 cycles of rowing in the coxless pairs and, a few hours later, the first 120 cycles of rowing in the eight; the latter sees the disappearance of coxless pair pattern. The coxless pair bowman (upper trace) was sitting at position 7 in the eight and the strokeman (lower trace) was sitting at position 8. The arrows indicate the strokes from which the force patterns in (b) are drawn. (b) Typical force patterns of the three phases described in (a). (upper trace) Coxless pair (arrow u in (a)). (middle trace) At the beginning of rowing in the eight (arrow m in (a)). (bottom trace) After 100 rowing cycles in the eight (arrow b in (a)). Dashed lines = force patterns of the strokeman and dotted lines = force patterns of the bowman.

the same pattern, whereas at other times they did not (see below). The individual form differences were generally similar in nature to the mean form difference; however, when increasing and decreasing individual form differences were seen simultaneously, the values for the increasing form differences were always lower than for the decreasing ones. In contrast, the individual area differences often showed non-systematic variation. Form differences and, to a lesser extent, total differences were lowest when mean area was high. This reduction in form differences appeared instantaneously when force output increased.

Case 3. An example of a reduction in form differences during the course of intensive training (32 strokes at race pace) is shown in Fig. 8. The mean total difference did not change because the mean area difference increased, owing to the divergent course of areas 2 and 4 versus 1 and 3 (Fig. 8, upper right). Analysis of individual form differences showed that the reduction in



Fig. 5. (a) Time course of mean total differences (MeanTotalDiff; top trace) and mean form differences (MeanFormDiff; bottom trace) for the first 45 min of rowing in training run V57. Both were lowest during the two 30 stroke intervals at race pace. The arrows indicate the strokes from which the force patterns in (c) are drawn. (b) The decrease in form differences over the first 150 strokes in training run V57. This was mainly the result of improved adaptation of the force pattern of rower 4. An increase in the centre of force (upper right), an improvement in smoothness of the force pattern (lower left) and an improvement in synchronization of the catch (lower right) resulted in a reduction in individual form differences (upper left). (c) The force patterns of the crew in training run V57 during different phases of the run. (upper trace) Endurance rowing with marked differences (arrow u in (a)). (middle trace) Endurance rowing with less marked differences (arrow w ria (a)). The force patterns are overlaid to demonstrate within-crew variation.

mean form differences was caused by a decrease in individual form differences of rowers 1, 2 and 3, while the individual form differences of rower 4 increased slightly (Fig. 8, lower left). Further analysis showed that the changes in form differences of rowers 2 and 4 depended mainly on changes in the centre of force



Fig. 6. (a) Time course of mean total differences (top trace) and mean form differences (bottom trace) for 90 min of rowing (1800 rowing strokes in total) in training run V512. Differences were least marked during intervals of 10 or 20 strokes at race pace (arrows at bottom). The labelled arrows indicate the strokes from which the force patterns in (b) are drawn. (b) The force patterns of different phases of training run V512. (upper trace) Endurance rowing with marked differences (arrow u in (a)). (middle trace) Endurance rowing with less marked differences (arrow m in (a)). (bottom trace) Rowing at race pace (arrow b in (a)). The force patterns are overlaid to demonstrate within-crew variation.

patterns (Fig. 8, lower right). Average values over the 32 strokes were almost identical for rowers 1, 2 and 4 but considerably higher for rower 3 (45.4, 44.8, 44.5 and 48.7 respectively). A decrease in the centre of force for rower 4 caused the increase in his form differences (r = -0.85). The decrease in form differences of rower 3 correlated strongly with the decrease in his centre of force value (r = 0.76), as well as with an improvement in the synchronization of the catch (r = 0.35). The reductions in the form differences of rowers 1 and 2 were not due to a change in their movement patterns, but did benefit from the change in movement pattern of rower 3. This changed the common force pattern of the crew, making it more similar to the patterns of rowers 1 and 2. Other variables, such as the smoothness of the force graphs and synchronization of the finish, did not contribute to these reductions in form differences.

In this training run (V56), the crew performed a second interval of 32 strokes at race pace, with a similar reduction in form differences.

The relationship between force output and differences in force patterns

Analysis of the mean areas showed that, in general, force output was higher during intensive intervals at race pace than in endurance intervals (see Table 1; compare the positive correlations between area and stroke rate in Table 2). This does not imply, however, that high stroke rates are necessary to develop a high force production. On the contrary, because of the physiology of muscle contraction, force production is higher when the speed of contraction is low (Hill, 1938; Kuechler, 1983). This occurs at lower stroke rates



Fig. 7. Time course of 180 rowing cycles in training run V44. A reduction in force output during endurance rowing (upper trace) resulted in more marked differences. Stroke rate was kept almost constant.



Fig. 8. An intensive rowing interval (32 strokes at race pace, indicated by vertical lines) in training run V56. Time course of mean differences (upper left). Divergent courses of individual areas (upper right) caused an increase in mean area differences (Mean-AreaDiff). The reduction in mean form differences (MeanFormDiff) was caused by a reduction in the individual form differences (FormDiff) of rower 3 (lower left), which was mainly the result of a decrease in the centre of force pattern (lower right).

when the speed of the shell and, therefore, the speed of movement and speed of muscle contraction is slower. Results from on-water rowing and ergometer rowing confirm this theory (H. Hill, unpublished results).

Table 2 also shows that form differences, but not area differences, were in general lowest during intensive intervals in the nine training runs with such intervals (46 intervals in total, including eight in run V58, in which the force patterns of three rowers only were recorded). The exceptions were one interval of 10 strokes in run V57 (Fig. 5a) and all six intervals of 10 strokes each in run V50. In run V50, the coach rowing in the bow produced very large individual form differences compared with the other three rowers. Compared with endurance rowing, there were more intensive intervals with reduced form differences than there were intensive intervals with reduced area differences (Wilcoxon test, n = 7, Z = 2.02, P = 0.043).

A correlation analysis was also performed to determine the relationships between area (force output) and form differences and between area and area differences. This analysis was based on the mean values of the different intervals of these parameters. Figure 9 shows the mean values of 10 intervals (five intensive and five endurance) for mean area, stroke rate, mean form differences and mean area differences in training run V467. Mean area and stroke rate were highly correlated (r = 0.87, P < 0.001) and mean area and mean form differences were highly negatively correlated (r = -0.93, P < 0.0001). There was only a weak and non-significant but positive correlation between mean area and mean area differences (r = 0.44, P = 0.21). This example demonstrates clearly that form differences, but not area

	Crew	Intensive intervals (n)	Intensive interval	s with differences	Correlation coefficients			
			less marked th rowin	an endurance $ng(n)$	Area * stroke rate	Area *	Ar 22 *	
Run			MeanFormDiff	MeanAreaDiff		MeanFormDiff	MeanAreaDiff	
V45	EFDM	2+1K	2	0	-0.08	-0.36	0.22	
V467	HLNA	5	5	0	0.87	-0.93	0.44	
V50	NMPJ	6	0	N.A.	0.97	0.1	N.A.	
V512	HLEC	11	11	2	0.87	-0.91	-0.56	
V534	DFGK	5	5	5	0.91	-0.98	-0.89	
V55	FDKG	3 + 4K	3 + 3K	2 + 2K	-0.72	-0.21	-0.17	
V56	FDKG	3	3	0	0.87	-0.95	0.21	
V57	OIMP	3	2	2	0.97	-0.63	-0.2	

Table 2. Number of intensive intervals around race pace with mean form and area differences lower than those in endurance intervals, plus correlation coefficients between mean area and stroke rate, mean form differences and mean area differences

Note: Intervals with high force output but very low stroke rates (10-15 strokes per minute) in V45 and V55 are indexed with a 'K'. When excluding these intervals, the correlation coefficients for area * stroke rate are 0.71 in V45 and 0.56 in V55. N.A. = not available. Crew members represented by letters (see footnote to Table 1).

differences, between force patterns depend on force output.

Comparing all training runs that included intervals of intensive rowing, with a single exception (run V50) mean area and form differences were negatively correlated, whereas mean area and area differences were either weakly negatively correlated or even positively correlated. Mean area and stroke rate were highly correlated, except in training runs V45 and V55; in both these runs, the crews performed intervals to improve technique, which encompassed high force outputs and very low stroke rates (below 14 strokes per minute), weakening the correlation.

Comparing the individual form differences with mean area of seven training runs (V50 excluded) in general revealed negative correlations, except for one rower in each of runs V45, V55 and V57. In contrast, a negative correlation between area differences and mean area was found in run V534 only. Positive correlations were found once in runs V512 and V55 and twice in runs V45, V467 and V56. Therefore, it can be concluded that the relationship between force output and form differences is systematic, but that between force output and area differences is random. In addition, the negative correlation between mean area and form differences was not restricted to the intensive training intervals with a high stroke rate, but also to endurance training intervals with stroke rate kept constant (see Fig. 7).

Discussion

In the present study, force patterns were recorded in 11 coxless fours training runs to examine the stability



Fig. 9. Mean values and standard deviations for mean area (MeanArea), stroke rate, mean form differences (Mean-FormDiff) and mean area differences (MeanAreaDiff) for the five intensive (black bars) and five endurance (grey bars) training intervals of run V467 in chronological order. The intensive rowing intervals (2 min at nearly race pace) can be identified by the higher stroke rates and higher areas. Standard deviations are higher for area differences during the intensive intervals, but higher for form differences during endurance intervals. This indicates that form differences but not area differences depend on force output.

and systematic and non-systematic variation of individual movement patterns and the interaction of crew members. It was hypothesized that crew members with similar force patterns, except in the coxed and coxless pairs, would result in a more efficient crew. It was expected that rowers with different force patterns would change towards a pattern that was common to all crew members.

There is little information on the drawbacks of having different force patterns. Two facts provide a quantitative contribution to this discussion. First, when a rower increases his force output during the drive phase, at odds with the rest of the crew, the speed of the shell will momentarily be increased. However, a portion of this additional force will be wasted by an increased slip of the blade in the water and a yawing of the shell. Secondly, the power developed by a muscle depends on the relationship between force and velocity of contraction (Hill, 1938). The maximum power output of a muscle is about 30% of the maximum isometric force, which must not be identical with maximal muscle efficiency (Hollmann and Hettinger, 1990). Therefore, momentarily increasing force production in contrast to the other members of a crew will cause the muscles to fall outside the effective range of the force-velocity curve.

In this study, a systematic reduction in differences between force patterns from the beginning to the end of the 11 training runs was not seen, although some crews did show a reduction. Crews with large differences that showed a decrease did not perform as well as crews who initially showed small differences. Thus it can be concluded that crews with crew members with similar force patterns will be more efficient. On the other hand, it can be assumed that crews have to row together for a long time before perfecting within-crew coordination. Frequent changes of crew members, as occurred in the present study, may hinder this process.

Smoothness of force patterns

The smoothness of the force patterns of novice rowers assessed on an ergometer (Hill *et al.*, 1995) was clearly inferior to that of elite rowers assessed both on the water and on an ergometer (Hill, 1995). This is in line with the results of Smith and Spinks (1995), who used a different method (based on fast Fourier transforms) to calculate smoothness in elite, good and novice rowers performing on an ergometer. The elite rowers in the present study did not see an improvement in their smoothness of force patterns during the training camps. It would appear, therefore, that much specific training is required to improve smoothness, one discriminating factor between rowers of different abilities.

Synchronization of the catch and finish

The differences in onset and end of force patterns between the rower at stroke, who determines the pace, and the remainder of the crew were similar or less than those reported by Schneider *et al.* (1978) and Wing and Woodburn (1995). Also, the lower values for the catch than for the finish are in line with the results of Angst (1976) and Schneider *et al.* (1978). There are two reasons why these values are lower for the catch than for the finish. First, the catch is the main trigger for following the rhythm of the crew member at stroke. Differences in individual stroke length (total rowing angle) will affect the finish. Secondly, the perception of the catch is easier because the force, in particular the slope of the force–time curve, is generally higher than at the finish. Therefore, during intensive training intervals with high force production, differences in synchronization will once more be reduced.

Centre of force patterns

Computing the centre of force patterns provides information about which part of the drive phase is stressed by the rower. In the present study, no systematic change was found, apart from a marginal but nevertheless significant difference between endurance and intensive rowing that was not analysed further. One coxless pair changed their asymmetric force pattern, which is necessary in this class, when rowing as part of an eight. It could be supposed that rowing in a four also requires an asymmetric pattern, but less pronounced as the boat is larger. However, in the present study no such pattern dependent on seating position was found. When rowers did change their seating position, their force pattern was nevertheless unchanged. The requirement of an asymmetric force pattern in the coxless fours is thus probably marginal. Because of insufficient data, it could not be determined whether this asymmetry is most marked between the stroke and bow positions.

The influence of force output on form differences

Both initially smaller and reductions in differences in force patterns were noted in those parts of training runs when force output was high; rowing with lower force output reduced crew coordination. This was a general finding when comparing intensive and endurance rowing. A reduction in form differences between force patterns was also seen in endurance rowing sections when force output was increased but stroke rate was kept constant, and in technical sections with very low stroke rates and high force output. It appears, therefore, that form differences are dependent on force output but not on the higher movement speed when stroke rate is high. The reduction in form differences can be explained by a decrease in the degrees of freedom when a movement is performed with increased force. Ideally, when all the muscles involved in performing the drive



Fig. 10. Possible variations in force patterns of the same rower. When force output is submaximal, different patterns are possible. The duration of the submaximal strokes is longer because both boat and body movement speeds are lower.

phase work maximally, only one movement pattern should be possible. However, in the submaximal range, considerable variation is possible because many of the muscles involved can be activated to different extents. Figure 10 provides such an example using the different force patterns of one rower. A reduction in the variation of force patterns will reduce within-crew form differences when force output is high.

In addition to this initial reduction in form differences, a further reduction was found during training only when force output was high. This can be explained by the better perception of form differences by the rowers. Little variation between individual force patterns will provide a more stable base for kinaesthetic perception because consecutive strokes will be more similar and the higher force production and speed of the boat will increase the inputs to the sensory system. Both processes will improve kinaesthetic perception and facilitate adaptation of the movement pattern. The better synchronization of the catch and finish when force output is high and the better smoothness of force patterns will also depend on these processes.

Different perception of form and area differences: a model

It was shown that changes in form differences and changes in area differences are not related. A reduction in form differences was found only when rowing with a high force output; individual form differences were in general similar to mean form differences. Area differences, on the other hand, were not related to force output and showed more variability among rowers. This is in line with the results of Mattes (1999), who reported variation in stroke power independent of absolute power and the success of the crew.

There are two processes that contribute to this divergence between area and form differences. First, any reduction in area differences during intensive rowing intervals by increasing force output will be dependent on the individual rower's physiological adaptability. The greater these individual differences are, the greater the area differences will be. On the other hand, the stronger rowers in a crew could reduce their force output to reduce area differences, although they probably do not. This leads to the second process: differences between the form of force patterns can be perceived better than differences between areas.

Increasing force output will increase the speed of the shell and, therefore, rates of change of rowing angle and joint angles; also, the speed of muscle contractions will be faster. The detection of muscle force at the Golgi tendon organs, joint angular velocity at the joint receptors and muscle contraction velocity at the muscle spindles will be integrated into a kinaesthetic perception of the force-velocity pattern of the drive phase of the rowing stroke. The model in Fig. 11 shows that this force-velocity pattern is different for area differences and for form differences. Because rowing angles were not measured in the coxless fours, Fig. 11 is modelled using force patterns and rowing angles in a single scull. However, this model needs to be validated in future studies using the force patterns and rowing angles of all rowers in a crew. Each point on the force pattern is assigned to a point on the angular velocity-time curve. Ideally in a smooth force pattern, each value of the force axis appears twice - before and after the maximum. Angular velocity will be higher for this second force value because the speed of the shell increases during the drive phase. When force patterns differ in form, the difference in the angular velocities assigned to the two identical force values will be greater than when the force patterns differ only in area. Therefore, within a single stroke there is great contrast between the two parts of the drive phase (before and after the maximum), which will facilitate the kinaesthetic perception of form differences. For example, the dotted line in Fig. 11 will make the rower feel that rowing is very exhausting in the first part of the stroke and very easy in the second part. In addition, a hydrodynamic effect can influence the perception of the force-velocity curve. Differences



Fig. 11. Force–time curves (above) and the resulting force– angular velocity curves (below) used as the basis for a model of the different perception of form differences and area differences between force patterns. A form difference between an individual force pattern (dotted line, upper left) and the common crew force pattern (dashed line) produces more marked differences in the force–angular velocity pattern during the drive phase (lower left) than an area difference between force patterns (upper right). In the latter case, the force–angular velocity pattern (lower right) remains almost unaltered.

between areas are built up mainly from force pattern differences in the middle of the drive phase. In this part of the drive, the movement of the blade perpendicular to the boat is only marginal, which produces more turbulence in the water surrounding the blade, leading the blade to slip in the water. The relationship between force output and movement speed will be weakened during the middle of the drive phase and disturb the perception of the movement pattern of the crew.

Conclusions

Two conclusions can be drawn for the building of successful rowing crews. First, crews should be composed of rowers with similar force patterns and similar physiological powers (with some limitations due to the specific demands of the coxed and coxless pairs). Secondly, to reduce force pattern differences, more effective rowing training should be performed at high force output. The physiological demands placed on the rower can be controlled by the stroke rate. This should be better for improving rowing technique than rowing with a low force output, as is often the case in training runs.

Because of the exploratory nature of this study, with non-systematic changes in combinations of crew

members and content of training runs, there was much variation in the interaction of the different variables derived from the force patterns to examine the coordination among crew members. This hampered statistical analysis; however, it provides direction for future hypothesis-guided studies.

Two additional tools to examine crew coordination should be used in the future. In the present study, the catch and finish sections of the force patterns were extrapolated to the baseline to remove the forces produced by oar movement and drag effects. However, the effects of drag have a negative influence and so should be minimized. An analysis of drag effects has an important role when investigating motor control and performance in rowing. The second tool is the averaging of force patterns (Wing and Woodburn, 1995; cf. Hill et al., 1995). Consistency and changes in movement patterns, the latter evoked in particular by adaptation when combinations of crew members are changed, can be assessed by comparing averaged force patterns and their standard deviations measured under different conditions. Because force pattern analysis is limited in its ability to describe coordination in rowing, additional measures should be used, such as rowing angle, movement of the sliding seat, forces applied to the stretcher and seat (cf. Lippens, 1992b) and the velocity and movement of the shell around its three axes.

Acknowledgements

The research reported here was funded in part by the German Federal Institute of Sports Science (Bundesinstitut für Sportwissenschaft, Köln, VF 0407/06/04/89). I wish to thank the oarsmen for their participation, Prof. Dr Christiane Buchholtz, Karl-Ludwig Damm and Dr Wolfgang Fritsch for their support, Dr Anja Holderbaum and Prof. Ken Holmes for proof reading and two anonymous reviewers for their critical comments, which helped me improve the manuscript.

References

- Adam, K., Lenk, H., Nowacki, P., Rulffs, M. and Schroeder, W. (1977). *Rudertraining*. Bad Homburg: Limpert.
- Altenburg, D., Boehmert, W., Fischer, J., Mattes, K., Rehbein, H. and Teller, P. (1996). Routinediagnostik im Deutschen Ruderverband. *Leistungssport*, 26, 53–58.
- Angst, F. (1976). Biomechanik des Ruderns. Unpublished diploma thesis, Technical University of Zurich (ETH).
- Atkinson, E.C. (1896). A rowing indicator. *Natural Science*, VIII, 178–185.
- Atkinson, E.C. (1898). Some more rowing experiments. *Natural Science*, XIII, 89–102.
- Fritsch, W. (1988). Zur Selektion und Fuhrung von Nationalmannschaften – einige Erfahrungen und Erkenntnisse. In *Rudern: Sportmedizinische und Sportwis*-

senschaftliche Aspekte (edited by J. Steinacker), pp. 293–298. Berlin: Springer.

- Galster, H. and Fritsch, W. (1988). Zum Problem der Rahmenplanung der Mannschaften im Spitzenrudern. In Rudern: Sportmedizinische und Sportwissenschaftliche Aspekte (edited by J. Steinacker), pp. 299–303. Berlin: Springer.
- Haenyes, B. (1984). Die biomechanische Leistungsdiagnose. *Rudersport*, **102**, 84–86.
- Hill, A.V. (1938). The heat of shortening and the dynamic constants of muscle. *Proceedings of the Royal Society of London, Series B: Biological Sciences*, **126**, 136–195.
- Hill, H. (1986). Zum Lernen von cyclischen Bewegungen beim Menschen am Beispiel von Ruderbewegungen. Unpublished diploma thesis, University of Marburg.
- Hill, H. (1995). Inter- und intraindividuelle Veraenderungen von Koordinationsmustern im Rudern. Regensburg: Roderer.
- Hill, H. (1997). Zur Auswirkung rudertechnischer Fehler auf die Renngeschwindigkeit – eine Untersuchung an zwei Fallbeispielen. In *Rudern – Erleben, Gestalten, Organisieren* (edited by W. Fritsch), pp. 113–123. Wiesbaden: Limpert.
- Hill, H., Damm, K.-L. and Buchholtz, C. (1995). Die Optimierung des Kraft-Zeit-Verlaufs des Ruderschlages durch objektives visuelles Feedback. In *Rudern – Lehren, Lernen, Trainieren* (edited by W. Fritsch), pp. 95–104. Wiesbaden: Limpert.
- Hollmann, W. and Hettinger, T. (1990). Sportmedizin: Arbeitsund Trainingsgrundlagen. Stuttgart: Schattauer.
- Ishiko, T. (1968). Application of telemetry to sports activities. In *Biomechanics I* (edited by J. Wartenweiler, E. Jokl and M. Hebbelinck), pp. 138–146. Basel: Karger.
- Ishiko, T. (1971). Biomechanics of rowing. In *Medicine and Sport Vol. 6: Biomechanics II* (edited by J. Vredenbregt and J. Wartenweiler), pp. 249–252. Basel: Karger.
- Ishiko, T., Katamoto, S. and Maeshima, T. (1983). Analysis of rowing movements with radiotelemetry. In *Biomechanics VIII-B* (edited by H. Matsui and K. Kobayashi), pp. 816–821. Champaign, IL: Human Kinetics.
- Koerner, T. and Schwanitz, P. (1985). Rudern. Berlin: Sportverlag.
- Kuechler, G. (1983). Motorik Steuerung der Muskeltaetigkeit und begleitende Anpassungsprozesse. Stuttgart: Fischer.

- Lippens, V. (1992a). Die Innensicht beim motorischen Lernen. Köln: Sport und Buch Strauss.
- Lippens, V. (1992b). Untersuchungen des Bewegungsverhaltens von Ruderanfaengern. Leistungssport, 22, 50–56.
- Lippens, V. (1999). The temporal and dynamic synchronization of movement in a coxless oared shell. In Sport Kinetics 1997: Theories of Motor Performance and Their Reflections in Practice, Vol. 2 (edited by P. Blaser), pp. 39–44. Hamburg: Czwalina.
- Mattes, K. (1999). Zur rudertechnischen Stabilitaet im 2000-Meter-Rennen. In *Rudern: Informieren, Reflektieren, Innovieren* (edited by W. Fritsch), pp. 188–199.
 Wiebelsheim: Limpert.
- Nolte, V. (1981). Zur Struktur des Kraftverlaufs als individuelles Merkmal beim Rudern. *Leistungssport*, 11(suppl. 26), 46–61.
- Roth, W., Schwanitz, P. and Pas, P. (1987). Zum Einfluss differenter Kraft-Zeit-Verlaeufe im Training auf die muskelzellulaere Anpassung. *Medizin und Sport*, **27**, 166–169.
- Roth, W., Schwanitz, P., Pas, P. and Bauer, P. (1993). Forcetime characteristics of the rowing stroke and corresponding physiological muscle adaptations. *International Journal* of Sports Medicine, 14(suppl. 1), S32–S34.
- Samsonov, E., Novikow, M. and Dratschewski, L. (1975). Bildung starker Auswahlmannschaften im Rudersport. *Rudersport*, 92 (Trainer Journal 40/41), VIII.
- Schneider, E. (1980). Leistungsanalyse bei Rudermannschaften. Bad Homburg: Limpert.
- Schneider, E., Angst, F. and Brandt, J.D. (1978). Biomechanics in rowing. In *Biomechancics VI-B* (edited by E. Asmussen and K. Jorgensen), pp. 115–119. Baltimore, MD: University Park Press.
- Smith, R.M. and Spinks, W.L. (1995). Discriminant analysis of biomechanical differences between novice, good and elite rowers. *Journal of Sports Sciences*, 13, 377–385.
- Williams, J.G.P. (1967). Some biomechanical aspects of rowing. In *Rowing: A Scientific Approach* (edited by J.P.G. Williams and A.C. Scott), pp. 81–109. London: Kaye & Ward.
- Wing, A.M. and Woodburn, C. (1995). The coordination and consistency of rowers in a racing eight. *Journal of Sports Sciences*, 13, 187–197.