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**ABSTRACT:** The present paper reports on an experimental activity carried out to develop a new on-water data acquisition system suitable for measuring performance in sculling/sweep rowing (i.e. to gather the most significant forces applied by the rowers to the shell as well as the relative displacement of the seat and the rotation of the oars). A preliminary study was carried out to single out the effective components of those forces resulting in the displacement of rowing shells, locating also the positions of the corresponding application points. According to the outcomes of this preliminary investigation different sensors were designed to gather, from any rowing station, the following pieces of information: effective magnitude of the propulsive forces parallel to the shell axis, oar rotation angle, vertical force applied to the seat by the rower, the relative position of the seat and, finally, the forces applied by the rower's legs to the footstretcher. Further, two accelerometers were used to measure acceleration and pitch of the shell. The accuracy and repeatability of the developed system and sensors were checked by carrying out several on-water acquisitions not only on standard shells (considering different crews), but also through an on-purpose built dry-land rowing station. To clearly show features and potentialities of such a data-acquisition system, the present paper reports on a series of tests carried out considering two different coxless pair crews, i.e. professional athletes and amateurs. The obtained results are definitely encouraging, proving that the pieces of information which can be gathered through our data acquisition system could be really helpful not only in evaluating rowers' characteristics in terms of athletic performance and technique, but also in designing innovative rowing shells meeting the specific requirements of a crew.

KEY WORDS: ergonomics, on-water measurement, rowing

#### NOTATION

as	Shell's acceleration
$p_{seat}$	Relative position of the seat
$t_{\rm i}, t_{\rm f}$	Initial and final instant defining a stroke
$v_{oar}$	Angular velocity of the oar
$F_{\rm eff}$	Effective force at the oarlock
$F_{\rm fs}$	Force perpendicular to the footstretcher
$F_{\rm m}$	Mean value of the effective force per stroke
Fseat	Force perpendicular to the seat
$F_{\rm tot}$	Total value of the average force per stroke

## Introduction

Competitive rowers are athletes having remarkable physical strength, high endurance and well-trained on-water technique [1, 2]. In rowing shells, the propulsive power, resulting in the displacement of the shell itself, is because of the forces generated, through the action of the oars, by the biological system (i.e. the rowers).

$F_{\rm R}$	Force at the oar handle					
$P_m$	Average value of the power supplied by a crew					
$P_j$	Power per stroke supplied by a crew					
$V_m$	Average velocity of the shell during a stroke					
Vs	Shell's speed					
α	Rotation of the oar					
$L_{\rm tot} = L_{\rm i} +$	Rotation of the oar $L_i + L_e$					
	Length of the oar					

To maximise the effective value of the applied forces, rowers make full use of their bodies: both the legs and the arms are cyclically extended and retracted and such movements are coupled with the rotation of the back (Figure 1A) [1, 2]. Even if at first the above coordination pattern could appear very simple and 'natural', a sophisticated rowing technique is always required to efficiently optimise the performance of the boat. This is complicated by the fact that, in the most



Figure 1: Schematic view of a rowing station and locations of the sensors

complex configurations, the resulting velocity of the shell depends also on the synchronism amongst the different rowers (up to eight athletes) as well as on their mutual compatibility (in terms of both athletic performance and technique).

Because of the difficulties of directly measuring the forces applied by the rowers during on-water runs, the performances of an athlete are usually evaluated through indoor simulators. Even if such a strategy can give useful indication on athletes' muscular and cardiovascular endurance, it does not allow any reliable verdict about their on-water efficiency to be expressed because of the fact that not only the feeling but also the body's movements are different. This is the reason why, since the early eighties, many different attempts have been made to develop integrated systems capable of measuring the forces acting on the blade as well as the rotation angle of the oar (Figure 2) - see, for instance, Ref. [3] and references reported therein. Furthermore, it is important to highlight here that the dynamic behaviour of rowing shells depends also on the forces applied by the athletes both to the footstretchers and to the seats (including their relative displacement) (Figure 1): it is

evident that all the above pieces of information have to be gathered simultaneously to efficiently evaluate not only the efficiency of any athlete but also the mutual interactions between rowers and shell.

According to the above considerations, in recent years a big effort has been made to develop reliable data acquisition systems suitable for measuring on-water rowing outputs, so that, nowadays there exist several devices ad hoc designed not only for research but also for commercial purposes. This makes it evident that the problem addressed in the present paper is not new at all: the work discussed in what follows represents nothing but an attempt to propose different solutions to those already available both in the technical literature and on the market. As to the use of the commercial sensors, it is important to highlight that, in general, they are installed by replacing some existing components (like, for instance, the oarlocks). On the contrary, our work takes as its starting point the fact that for professional athletes the set-up of their rowing stations strongly affects their performances, therefore the data acquisition system we developed was designed not to alter the set-up when measuring the parameters of interest.



**Figure 2:** Forces at the oar and definition of rotation angle  $\alpha$ 

In more detail, different sensors were designed so that they can directly be attached to rowing shells without the need for replacing any of the existing parts. Such sensors allow the forces applied by the rowers to the footstretchers, the oars and the seats as well as the rotation angles of the oars and the relative positions of the seats to be measured.

To conclude, it is worth noticing that accuracy and reliability of the developed on-water data-acquisition system were checked by considering different rowers as well as different types of shells, i.e. by investigating not only professional athletes, but also amateurs: this paper then summarises the main outcomes of a research activity which has been carried out over the last 4 years.

## The State of the Art: A Brief Review

Examination of the state of the art shows that the rowing problem has been investigated mainly considering three different aspects: (i) prediction of boat speed, observed forces and motions, (ii) biomechanical parameters of ergometric rowing and (iii) definition of indices suitable for evaluating on-water performances of rowers. As to aspect (i), the first systematic investigation on the mechanics of rowing was carried out by Alexander in 1925 [4]. In his pioneering study, he devised a sophisticated mono-dimensional model capable of describing the shell motion by directly estimating coordination patterns for legs, arms and back of the rower as well as the oar's angular velocity. The above model is based on the hypotheses that the rower can be schematised as a point mass and the oar as an infinitely stiff bar. Moreover, in the calculation Alexander considered also a fictitious mass of the boat which accounts for the effect of the water flowing around the shell.

By taking as a starting point the above pioneering mono-dimensional model, since the early seventies, many researchers have attempted to propose more sophisticated approaches to describe and predict rowing shells' motion. For instance, Pope [5] formalised his approach by assuming a linear law between angular velocity of the oar and relative velocity of the rower's centre of mass. Moreover, he proposed an interesting 'propulsive efficiency index' defined by considering the effective work done at the blade, i.e. calculated along the motion direction, and the power at the oar handle. Both Van Holst [6] and Atkinson [7] included in the calculation the drag as well as the lift forces on the blade, considering also the inertia of the oar. Furthermore, Atkinson [7] took into account the flexibility of the oar as well. Even if several other approaches attempting to describe the mechanics of rowing have been formalised and somehow validated by experimental data [8–14], as observed by Cabrera *et al.* [15], 'with exception of Atkinson who accurately predicts boat velocity, none of these models is shown to accurately predict observed forces and motions'.

After examining the state of the art, Cabrera, Ruina and Kleshev [15] proposed an accurate model which represents nothing but a sophisticated development of the classical one because of Alexander [4]. In more detail, to formalise their inverse dynamic approach, the above authors used one-dimensional momentum balance, point mass rowers, infinitely stiff oar shafts with inertia and non-infinitesimal stroke angles. Moreover, they adopted quadratic law for the force versus speed relationships of both the rowing shell and the oar blade.

As to the aspects related to ergometric training, initially it has to be said that a big effort has been made to provide athletes with reliable systems suitable for gathering and post-processing quantitative information regarding kinematics, kinetics, performance and form [16-27]. Unfortunately, the wellknown differences between on-water and dry-land rowing techniques [28, 29] suggest that ergometric training must be monitored carefully by experienced coaches not to have a reduction of the athlete's effective performances. For instance, Torres-Moreno, Tanaka and Penney [30], by measuring joint excursion, handle velocity and applied force in 44 different athletes during 2500 meter runs on an instrumented ergometer, came to the conclusion that an excessive indoor training could result in a reduction of the rowers' on-water performances. Moreover, Steer, McGregor and Bull [29] proved that the use of different ergometers can result in different repeatability of the rowers' technique in terms of spinal kinematics and applied force, affecting body form. This aspect is very important also because it was seen that different rowing techniques are associated with different incidences of low back pain [31, 32].

The models reviewed at the beginning of the present section allow the velocity of the boat to be predicted with a reasonable level of accuracy. Another aspect of the problem which deserves to be mentioned here is the adoption of appropriate indices suitable for evaluating on-water performance of rowers: if such indices are correctly defined, they should allow the overall efficiency of rowing shells to be increased by giving useful indication not only

on the characteristics of an optimised crew but also on specific training programs for the athletes [33]. According to the importance of such an analysis, several attempts have been made to propose reliable and meaningful efficiency indices. The state of the art shows that all the proposed parameters take as a starting point the idea that the final time of a rowing shell in a run is the parameter which must be optimised, because it represents an indirect measure of the propulsive power supplied by the athletes.

As the final time is equal to the distance covered during the run divided by the average velocity of the shell, which can be expressed also as the average velocity during one stroke times the number of strokes in a run, Schneider and Hauser [34] suggested evaluating on-water performance by focusing attention on the events occurring during one single cycle (i.e. during the coordination pattern from frontstops to backstops and vice-versa).

By following a different strategy, Asami, Adachi and Yamamoto [35] as well as Nozaki, Kawakami, Fukunaga and Miyashita [36] proposed to evaluate rowing efficiency as the ratio between the total mechanical work done by an athlete and his oxygen requirement.

Finally, Badouin and Hawkins [37] attempted to calculate an efficiency index by linearly interpolating the total propulsive power, the synchrony of the forces applied to the oars and the total drag contribution, where the above quantities were estimated from the rowers' force versus time curves and recovery kinematics. To determine the necessary quantities they gathered, in a coxless pair shell, the bending force and the rotation angle of the oars, the relative position of the seats and, finally, the velocity of the shell. The most interesting outcome of such an accurate experimental investigation is that total propulsive power, synchrony and total drag contribution are quantities suitable for evaluating but not for predicting the efficiency of a rowing crew. Moreover, it was seen that there exists an evident mutual interaction amongst the athletic characteristics of the rowers and such an interaction strongly affects their force-time profiles.

In this complex scenario, the present paper reports on an investigation we carried out to formalise a procedure suitable for evaluating on-water performance of rowers by post-processing pieces of experimental information gathered by using a new data-acquisition system we have developed in our laboratory by working in collaboration with Cantiere Navale Filippi Lido S.r.l. (http://www. filippiboats.it).

### The On-Water Data-Acquisition System

To develop an efficient data-acquisition system, a preliminary theoretical study was carried out to single out those physical quantities suitable for evaluating sculling/sweep on-water performance of rowers. In more detail, taking full advantage of the models devised by both Alexander [4] and Cabrera, Ruina and Kleshev [15], the effective components of those forces resulting in the displacement of rowing shells were analysed, locating also the positions of the corresponding application points. To check the validity of the assumptions made to determine those hot-spots suitable for being used to efficiently measure the quantities of interest as well as to evaluate the magnitude of the forces involved in sculling/sweep rowing, a preliminary study was carried out by directly attaching strain gages to the different parts of a standard station of a double scull shell. In more detail, the in-service local deformations of the following components were measured (see Figures 1 and 2): oarlock pin, wing rigger, backstay, seat and tube supporting the footstretcher. The oar rotation angle, the relative displacement of the seat as well as the acceleration of the shell and its pitch were also evaluated during different sequences of strokes. This preliminary experimental study allowed us to confirm the validity of the assumptions made to single out those quantities to be used to evaluated the propulsion power supplied by rowers as well as to have a direct measurement of the magnitude of the forces involved in the process.

According to the outcomes of the above preliminary investigation and to correctly design the sensors to be used during on-water data-acquisition, attention was then focused on the following components (see Figures 1 and 2): wing rigger, oarlock, seat and footstretcher. In more detail, it was decided to measure the forces parallel to the shell axis, F<sub>eff</sub>, and resulting in the displacement of the shell itself, through the deformation of the wing riggers, the oar rotation angle,  $\alpha$ , through the rotation of the oarlock, the vertical force applied to the shell by the rower,  $F_{\text{seat}}$ , through the deformation of the seat, the athlete inertia through the relative position of the seat,  $p_{\text{seat}}$ , and, finally, the force applied by the rower's legs,  $F_{fs}$ , through the deformation of the aluminium tube supporting the footstretcher. Two accelerometers were also used to measure acceleration and pitch of the shell. Finally, for on-water measurements a National Instruments CompactRIO<sup>®</sup> (National Instruments, Austin, TX, USA) programmable automation controller [together with LabVIEW (National Instruments) graphical programming language] was used to develop an appropriate data-acquisition system.

The geometry of the sensors was optimised by performing a series of tests using not only a standard double scull shell (Figure 3A) but also a dry-land station which was on purpose built in our laboratory to experimentally check the accuracy of the gathered pieces of information (Figure 3B). To record the data from the dry-land station not only the National Instruments CompactRio<sup>®</sup> controller but also a HBM Spider 8 multi-channel electronic PC measurement unit were used: this experimental strategy allowed us to check the robustness of the new data-acquisition system developed on National Instruments technology.

By following the above iterative design process, we eventually reached an optimised configuration of our on-water measurement unit: the effective components of the forces applied by the rowers both to the wing riggers (Figure 4A–C), to the seats (Figure 4D) and to the footstretchers (Figure 4E) are measured through  $\Omega$ -shaped thin strips of harmonic steel, whose deformations are directly gathered by means of strain gages in full-bridge configuration. Further, the optimum curvature of such sensors was determined by doing a series of Finite-Element models



**Figure 3:** Double scull shell with sensors (A) and dry-land station designed to experimentally check accuracy and reliability of the developed sensors (B)



Figure 4: Overview of the developed sensors

(Figure 5). Oar rotation angles are measured by using 308° rotary potentiometers (Novotechnik SP2831; Novotechnik, Southborough, MA, USA) that are directly attached to the oarlocks (Figure 4F,G); the relative position of the seats (Figure 4H) is measured by using string potentiometers (CELESCO SP2-50; CELESCO, Chatsworth, CA, USA); acceleration and pitch of the shell are evaluated by post processing the signals from two triaxial accelerometers. Lastly, the unit is also equipped with a Wi-Fi signal acquisition device for real-time data display and analysis.

The final result of the optimisation process briefly summarised above is a flexible and relatively light integrated system whose sensors can directly be attached to any type of shell without altering the setup of its rowing stations. Moreover, to accurately evaluate on-water performance no sensors have to be attached to the athletes' body, allowing them to row without any interference with their normal coordination pattern.

# Sensors' Accuracy/Repeatability and their In-Field Calibration

After optimising the geometries of the sensors briefly described in the previous section, initially the linearity and repeatability of the generated signals as well as their accuracy in measuring the mechanical quantities of interest were evaluated by running appropriate tests in our laboratory.

Figure 6 shows the set-up of the different tests we carried out. In more detail, the characteristics of the sensors devised to measure  $F_{\text{eff}}$  were investigated by



**Figure 5:** An example of the FE analyses carried out to define the optimum curvature and dimensions of any designed  $\Omega$ -shaped sensor

testing both composite material (Figure 6A) and aluminium wing riggers (Figure 6B) which were directly attached to a stiff vertical beam. The magnitude of the loading vertically applied to the oarlock was measured by using a commercial loading cell. The diagram reported in Figure 7 makes it evident that the response of the  $\Omega$ -shaped sensors was practically linear, the curve obtained by testing the composite material wing rigger being characterised by a little hysteresis phenomenon.

The same loading cell was also used to investigate the linearity of the sensors specifically designed to measure the force perpendicularly applied to the footstretcher by the rower (Figure 6C): as clearly shown by the measured strain versus applied loading curve reported in Figure 7, also the behaviour of such a sensor was seen to be characterised by an high level of linearity.

Finally, the response of the sensor attached to the seat was also investigated in depth. As shown in Figure 6D the loading was perpendicularly applied to the seat by placing a 'pillow-like apparatus' between the loading cell and the seat itself to have a distribution of the pressure closer to that observed in reality. As the sample we tested in our laboratory was a sandwich carbon fibre reinforced seat, its behaviour was seen to be quite particular: as clearly shown by the diagram reported in Figure 7, the gathered strain versus applied loading curve was characterised by two different slopes, the hysteresis of the loading/ un-loading curve becoming evident in the region 500–1000 N. In spite of the above particular



**Figure 6:** Loading-unloading tests carried out on wing riggers made of both composite material (A) and aluminium (B), on the footstretcher (C) as well as on the seat (D) to investigated linearity and repeatability of the designed sensors



**Figure 7:** Measured strain versus applied loading curves experimentally obtained to investigate the linearity as well as the repeatability of the designed sensors

response, it was assumed that the designed sensor could be in any case used to measure  $F_{\text{seat}}$  by simply calibrating it through a bi-linear measured strain versus applied loading function.

The high level of flexibility of the system we developed should make it evident that, to correctly evaluate the magnitude of the measured forces, all the sensors must be calibrated whenever they are attached to a new rowing shell, therefore a big effort was made also to formalise a simple and efficient infield calibration procedure. In more detail, the sensors measuring  $F_{\text{eff}}$  are calibrated by applying an horizontal loading to the oarlocks (Figure 8A) through a beam directly attached to the shell as well as through a threaded cylindrical bar (Figure 8B,C).

The magnitude of the applied loading is directly measured by means of a commercial loading cell. In light of the way they work, it is important to high-light that the accuracy of the above sensors in measuring  $F_{\text{eff}}$  is not affected by the position at which they are attached to the wing riggers (provided that they are correctly calibrated): it is evident that to amplify the signal as much as possible it is always advisable to place them as close as possible to the shell.

As the beam attached to the boat and used to calibrate the above sensors is perpendicular to the shell longitudinal axis, such a beam is used also as reference line to calibrate the rotary potentiometers used to measure the rotations of the oars: the calibration is done by using three different reference orientations, i.e.  $\alpha = 90^\circ$ ,  $0^\circ$  and  $-90^\circ$ .

The calibration of the sensors measuring the force applied by the rowers' legs to the footstretchers is performed instead by applying a ramp force perpendicular to the footstretchers themselves, where the magnitude of the applied loading is again measured by using a commercial loading cell (Figure 8D).

Finally, as they are the most tricky ones, the sensors measuring the forces perpendicular to the seats are calibrated by following two different strategies: by placing a series of weights on the 'pillow-like



Figure 8: In-field calibration of the sensors

apparatus' (Figure 8E) as well as by gradually pushing a loading cell against the seat itself (Figure 8F).

To conclude, it is interesting to highlight that all the necessary calibration functions are directly calculated by an *ad hoc* software we developed by using LabVIEW graphical programming language, and such a software is directly interfaced with the tool used to handle the signals recorded during on-water acquisitions.

## On-Water Measurement of Performance in Rowing: A Practical Example and a Preliminary Analysis

To check the on-water accuracy and repeatability of the developed data-acquisition system, several experimental analyses were carried out considering different types of rowing shells as well as crews characterised by different technical and athletic levels: over the last 4 years we have investigated the performances of more than 20 athletes, considering not only different types of shells but also different techniques (i.e. athletes from different European Countries).

As an example, the present section reports on two series of data gathered from Filippi double scull rowing shells equipped, according to FISA regulations, with the same components. This experimental investigation was carried out by considering both professional athletes and amateurs and, of course, any investigated rower was allowed to calibrate the set-up of his rowing station according to his own characteristics. Even if the considered rowers had similar physique (i.e. weight in the range 75–85 kg and height in the range 1.72-1.85 cm), the two crews were different in terms of both physical strength, endurance and on-water technique: this allowed us to better investigate the peculiarities of our data-acquisition system. It is also interesting to observe that all the considered oarsmen, even if characterised by different levels of technique, were capable of keeping the blades correctly immersed in the water at the point of maximum loading, that is, when the oars were perpendicular to the shell longitudinal axis.

The data were gathered during 500 m runs, where acquisitions started from a stationary configuration to easily calculate the absolute velocity of the shells by numerically integrating the acceleration versus time signal. During each acquisition session, the different channels were recorded with a frequency equal to 100 Hz, by subsequently filtering them at 10 Hz through a second order Butterworth filter.

According to the scopes of the present investigation, the strokes in the initial and final part of every run were not considered, so that, attention was focused on the central part of the runs (i.e. on a distance of approximately 300 m).

Finally, it is worth mentioning that, to have pieces of information which could be directly compared with each other, all the data discussed in what follows were gathered in sunny days and in the absence of wind, flowing and waves.

To conclude, as an initial example, Figure 9 reports the different signals gathered, in both crews, from station 1 (see Figure 3A) over a time interval of 6 s.

#### Analysis of the profiles of the gathered signals

To show the potentiality of the developed dataacquisition system, attention can initially be focused on the charts of Figure 9. Such diagrams clearly show that the signals characterising the performance of the professional athlete are much more regular than the corresponding ones of the amateur. Moreover, and as expected, the forces generated by the professional athlete have higher magnitude, with a larger stroke frequency.

Even if the professional athlete was very well trained, the direct comparison between the two forces measured at the two wing riggers,  $F_{\text{eff}}$ , shows that the force applied by the right hand to the oar is remarkably higher that the one applied by the left hand: this was because of a muscular problem and, as suggested by the coach himself, such an athlete should calibrate the dry-land training to strengthen his left arm to recover from the above problem. On the contrary, the amateur is seen to be much more balanced from this point of view.

Another interesting difference between the two rowers is that, while the  $F_{\text{eff}}$  versus time curves of the professional athlete show that a force opposing to the shell's motion is generated during the coordination pattern from backstops to frontstops, during the same pattern  $F_{\text{eff}}$  of the amateur is always equal to zero. This suggests that an attempt could be made by the professional athlete to reduce the above negative contribution by focusing attention on the way he makes the blades interact with the water (catch a crab!).

As to the cyclic coordination patterns of the two rowers, it is interesting to highlight that the  $\alpha$  versus time as well as  $p_{seat}$  versus time curves are characterised by a very regular profile independently from the characteristics of the rower himself. This experimental evidence could be ascribed to the fact that the rowers of a crew naturally tend to synchronise with



Figure 9: Examples showing the different signals gathered during the tests (rower 1 in both crews)

each other to have a good feeling both with the other members of the crew and with the shell. This implies that the relative position of the seat,  $p_{\text{seat}}$ , as well as

the oar's rotation angle,  $\alpha$ , are parameters suitable for evaluating the dynamic behaviour of a shell, but they cannot be used to express any reliable verdict about

the overall quality of the on-water technique of a rower.

The profile of the  $F_{\text{seat}}$  versus time curve of the professional athlete shows that a vertical force is always applied to the boat during the patterns from backstops to frontstops and vice versa. On the contrary, the amateur, in attempting to increase the magnitude of the force applied to the oar handles, tends to raise his bottom from the seat after reversing at the frontstops: this results in the fact that when  $F_{\text{eff}}$  is approaching its maximum value,  $F_{\text{seat}}$  tends to zero, showing an horizontal plateau.

Finally, it can be highlighted that the acceleration signal associated with the professional athlete is much more regular than the one associated with the amateur. It is evident that the profile of the above curve is affected by the overall characteristics of the crew, so that, it cannot be used to evaluate the efficiency of a single rower (unless this information is gathered from a skiff).

To more accurately investigate the rowing characteristics of the above two rowers, attention can be focused now on a 30-s time interval extracted from the intermediate zone of the analysed runs (Figure 10). The  $F_{\text{eff}}$ -right hand versus  $F_{\text{eff}}$ -left hand diagram of the professional athlete clearly shows that, contrary to the amateur, the forces are uniformly applied to the oar handles by the two hands during the coordination patterns, even if they are characterised by different maximum values. Moreover, the  $\alpha$ -right hand versus  $\alpha$ -left hand chart of the professional athlete makes it evident that, to keep the two blades at the same level with respect to the water, the shift angle between the oars becomes different from zero when they are almost perpendicular to the shell's longitudinal axis, i.e., when  $\alpha$  approaches zero (see Figure 2). On the contrary, the fact that for the amateur such a shift phase is always equal to zero during the coordination patterns suggests that the relative position of his hands is not correct, so that, the blades work at slightly different levels with respect to the water.

It is evident that the signals gathered by using our data-acquisition system can also be post-processed, or, in any case, combined in different ways, to obtain other pieces of quantitative information about the analysed crew. For instance, the charts of Figure 11 show that, over a series of strokes, the  $F_{\text{eff}}$  versus  $\alpha$  profile of the right hand of the professional athlete is different to the one of his left hand, even if the rotations of the two oars are characterised by the same angular velocity,  $v_{\text{oar}}$ . The above figure makes it evident also that the  $v_{\text{oar}}$  versus  $\alpha$  curves of the amateur are not only characterised by lower



**Figure 10:** Comparison between effective forces,  $F_{\text{eff}}$ , as well as between oar's rotation angles,  $\alpha$ , of a rower (station 1 in the two considered crews)



**Figure 11:** Effective force,  $F_{\text{eff}}$ , and angular velocity of the oar,  $v_{\text{oar}}$ , plotted against rotation angle,  $\alpha$  (station 1 in the two considered crews)

values of the maximum angular velocity compared with the corresponding ones of the professional athlete, but they are also quite irregular, the pattern of the left hand being more critical than the one of the right hand. Furthermore, the maximum and minimum values of angle  $\alpha$  at the right-hand side of the amateur are different to the corresponding values at his left-hand side: this suggests that, when moving from the backstops to the frontstops and the other way around, the amateur rotates the shoulders. On the contrary, the maximum and minimum values of the oars' rotation angles are always the same for the professional athlete, proving that he correctly keeps his shoulders always perpendicular to the shell's longitudinal axis during the stroke.

The data-acquisition system we developed allows also the performance of different rowers belonging to the same crew to be compared directly. For instance, the  $F_{\text{eff}}$ -Rower 1 versus  $F_{\text{eff}}$ -Rower 2 diagram reported in Figure 12 show that, on the right-hand side, the magnitude of the forces applied by the two professional athletes to the oar handles increase and decrease by following a regular and balanced path, even if with slightly different application rates. On the contrary, the same diagram built for the amateur crew makes it evident that, even though the forces are characterised by the same maximum and minimum values, the application rates of  $F_{\text{eff}}$  are remarkably different during the stroke.

To conclude, it is worth observing that the considerations reported in the above paragraphs were based mainly on the instantaneous values of the gathered signals. It is evident that such data can also be post-processed to calculate mean values, maximum values, minimum values, etc. Moreover, they can also be fully described from a statistical point of view, giving quantitative information about the performance of a rower. As an example, Table 1 summarises the results of the statistical reanalyses done considering the 30 s time interval plotted, in different ways, in the diagrams of Figures 10-12: the values listed in the above table fully confirm the validity of the considerations summarised in the present subsection also from a quantitative point of view.

#### Rowers' on-water efficiency

The overall performance of a rowing shell depends on a number of variables which should be taken into account simultaneously to correctly evaluate the



**Figure 12:** Comparison between effective forces,  $F_{\text{eff}}$ , as well as between the oar's rotation angles,  $\alpha$ , of the two rowers on the same shell

efficiency of a crew. According to the schematic drawing reported in Figure 13 (which, for the sake of clarity, trivialises the complexity of the addressed problem), the propulsive forces applied by the rowers through the oars result in a certain velocity of the shell, whose value is influenced in turn by other parameters, like (i) athletic dynamic performance of the rowers, (ii) compatibility amongst the rowers in terms of both technique and athletic characteristics, (iii) interaction between crew and shell; (iv) technical specifications of the shell, (v) interaction between shell and water and, finally, (vi) environmental conditions.

In spite of the large number of variables affecting the resulting velocity of a shell, the present subsection attempts to propose a simple way to evaluate the on-water performance of a crew by post-processing the pieces of experimental information which can directly be gathered by using the data-acquisition system we have developed. It is not superfluous to highlight here that to have meaningful information from the above analyses the performances of different athletes should be compared in environmental conditions as similar as possible. According to this fact, and as briefly said at the beginning of the present papers, this is the reason why many attempts have been made to evaluate performances of rowers by using different approaches allowing the above problems to partially be overcome (for instance, by using oxygen requirement [35, 36]).

Initially, it is trivial to observe that the instantaneous value of the shell's velocity,  $V_s(t)$ , can be determined not only by direct measurement (i.e. through instrumented propellers), but also by integrating the acceleration versus time signal.

Another aspect which deserves to be highlighted here is that, according to Schneider and Hauser [34], the overall efficiency of a crew can efficiently be evaluated also by considering the sequence of events occurring during every single stroke.

According to the above remark, the mean value of the effective force per stroke generated by an athlete can then be calculated from the corresponding  $F_{\text{eff}}$  versus time signals as follows:

$$F_{m,j} = \frac{1}{t_{\rm f} - t_{\rm i}} \int_{t_{\rm i}}^{t_{\rm f}} F_{\rm eff}(t) \mathrm{d}t,\tag{1}$$

where  $t_i$  and  $t_f$  are the initial and final instant, respectively, delimiting the *j*-th stroke. It is evident that the above quantity can be calculated for every considered rower, splitting also the actions of the two

Table	I: Some representative	values of the rowing	parameters measured	over the co	nsidered 30 s time	interval (Rower 1)
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	Professional athlete		Amateur			
	Oars					
Measured parameter (unit)	Right-hand side	Left-hand side	Right-hand side	Left-hand side		
Average value of $\alpha_{min}$ (degrees)	-60.5	-59.9	-74.3	-83.2		
Average value of $\alpha_{max}$ (degrees)	39.3	39.1	39.8	34.5		
Average value of $\Delta \alpha = \alpha_{max} - \alpha_{min}$ (degrees)	99.9	99.0	114.2	117.7		
Mean stroke frequency (Hz)	0.67	0.67	0.48	0.48		
Average recovery time (s)	0.698	0.679	0.873	0.866		
Rowing period (s)	1.472	1.473	1.805	1.805		
Average stroke rate (degree/s)	129.1	124.7	122.5	125.4		
Average value of $F_{\rm eff}$ (N)	406.2	317.7	156.4	189.2		
Maximum value of $F_{\rm eff}$ (N)	804.3	626.6	490.3	439.9		
	Seat					
Average value of $\Delta p_{\text{seat}}$ (cm)	42.2		59.2			
Average value of $F_{\text{seat}}$ (N)	395.1		307.7			
Maximum value of $F_{\text{seat}}$ (N)	803.9 729.4					
	Footstop					
Mean value of $F_{\rm fs}$ (N)	545.7		308.8			
Maximum value of $F_{\rm fs}$ (N)	1165.4		729.4			



shell and water

**Figure 13:** Simplistic schematisation adopted to define those variables affecting rowing shells' performance

oars in double scull shells. Moreover, it is straightforward to calculate the total value of the average force per stroke considering the contributions of all the athletes in the crew as follows:

$$F_{\text{tot},j} = \sum F_{m,j} \tag{2}$$

The second important parameter which can be used to evaluate on-water performance of a crew is the average velocity of the shell during the *j*-th stroke as follows:

$$V_{m,j} = \frac{1}{t_{\rm f} - t_{\rm i}} \int_{t_{\rm i}}^{t_{\rm f}} V_{\rm s}(t) {\rm d}t$$
(3)

It is important to notice here that, while the effective value of the applied force can be computed for every considered rower separately, the contribution of a single athlete to  $V_{m,j}$  cannot be determined because, if attention is focused only on the biological system, the resulting velocity of the shell depends not only on the athletic characteristics of every rower, but also on their mutual technical compatibility (Figure 13).

Bearing in mind the remark reported in the previous paragraph, the quantities defined above allow the power per stroke supplied by the crew to be defined as follows:

$$P_j = V_{\text{tot},j} \times F_{\text{tot},j} = V_{\text{tot},j} \times \sum F_{m,j}$$
(4)

As an example, in Figure 14 the power generated by the two crews already considered in the present section (i.e. professional athletes and amateurs) are directly compared considering the strokes in a 30-s time interval extracted from the central part of a 500-m run. It is evident that the chart of Figure 14A reports a larger number of strokes than those shown in Figure 14B simply because the stroke frequency of the athletes was higher than the one of the amateurs. According to the above diagrams, the average value of the power supplied by the professional athlete, calculated as:



**Figure 14:** Power versus number of strokes diagrams over a time interval of 30 s for the two investigated crews (R1 = Rower 1; R2 = Rower 2; RH = right hand; LH = left hand)

$$P_m = \frac{\sum_{j=1}^{k} P_j}{k},\tag{5}$$

where k is the number of strokes in the considered time interval, was equal to about 3.5 kW, whereas it was equal to about 1.8 kW for the amateur crew. Even if the definitions adopted to calculate  $P_j$  and  $P_m$ are very intuitive, the diagrams of Figure 14 should make it evident that this strategy allows on-water efficiency of rowers to be quantified in a very simple and direct way (and it can be done, of course, by considering not only the power per stroke,  $P_j$ , but also the average power over a certain number of strokes,  $P_{mv}$  therefore investigating different parts of a run).

Moreover, the same reasoning could be followed also to directly evaluate the contribution of every single athlete to the overall performance of the shell: the chart of Figure 14B shows that, even if characterised by a lower value of the supplied propulsion power, the two amateurs were well balanced, having comparable athletic performances; on the contrary, the diagram of Figure 14A shows that rower 1 was more effective than rower 2, giving a higher contribution to the resulting velocity of the shell. Moreover, the same diagram, further confirming what already discussed in the previous section, proves that rower 2 was unbalanced in terms of forces applied by his arms to the two oars.

#### **Summary and Discussion**

The present paper summarises the initial part of a long-term research activity aiming to develop a new on-water data acquisition system suitable for evaluating not only performance in rowing, but also the athletic profile of a rower in terms of those forces and displacements characterising the coordination pattern from frontstopts to backstops and vice versa.

To design efficient sensors to gather the necessary pieces of information, a preliminary study was carried out with the aim of singling out the most relevant forces involved in the rowing process, by also defining their application points. Thanks to this initial analysis, the sensors were designed so that the quantities of interest could accurately be measured without altering the set-up of the rowing stations: this aspect is very important especially for professional athletes because, due to the high level of specialisation, they are highly sensitive to the microadjustments of the components making up their rowing stations.

According to the preliminary investigation discussed in the present paper and done by considering both a professional and an amateur crew, initially our new on-water data acquisition system proved to be capable of giving pieces of information which can help coaches in optimising both on-water and dry-land training. As to the latter aspect, the gathered parameters, if correctly interpreted, can efficiently be used to design specific training programs suitable for optimising athletes' kinematics, kinetics, performance and form. As to the on-water coordination pattern, our data-acquisition system can be employed to have useful suggestions to bring changes to the technique of a rower to optimise the way power is supplied during a stroke: it is evident that in the presence of macroscopic mistakes coaches can directly correct them, on the contrary, when the changes to be made are very little, only sensitive instruments can give useful information regarding this aspect.

Another interesting feature of our on-water data acquisition system is that it can help athletes in optimising the set-up of their rowing station: in high level competitions, that is, when very well trained athletes are involved, optimising every single detail can make a substantial difference.

The signals gathered from the investigated crews were also used to check the validity of a strategy we have proposed to measure performance in rowing. According to Baudouin and Hawkins [37], the simple methodology we have devised takes as a starting point the idea that, when two or more rowers are considered, the overall performance of a single athlete cannot be predicted because it is strongly affected by the other internal and external parameters involved in the rowing process. The above fact resulted in the need for defining the power supplied by the biological system by forming the hypothesis that the contributions in terms of shell's velocity given by the single rowers belonging to a crew can not be uncoupled. According to the investigations we carried out, not only considering the crews discussed in the present paper, but also other crews analysed under different circumstances, it seems that such a simple modus operandi can give useful information about the overall performance of a group of athletes. This suggests that such an approach could successfully be used to form an optimised crew by choosing the most compatible ones among several available athletes.

To conclude, it is worth noticing that the data acquisition system we have developed can also be employed to design *ad hoc* shells meeting the requirements of a specific crew: the results we have obtained so far are very encouraging, allowing us to have useful indications not only to design innovative rowing boats, but also to define new geometries for the different components making up rowing stations.

## Conclusions

- 1 The developed on-water data acquisition system seems to be very effective not only in giving quantitative measurement of rower's coordination patterns, but also in evaluating the overall performance of the 'crew + both' dynamic system;
- **2** If correctly interpreted, and according to the athletic and physiological characteristics of the investigated rower, the signals gathered from a station could allow dry-land training to be calibrated in a more effective way;
- 3 The signals describing the coordination patterns could be used to modify the technique of an athlete to maximise his on-water efficiency;
- 4 Even if it is very simple and intuitive, the efficiency index proposed in the present investigation could be used not only to evaluate on-water performance of both athletes and shells, but also to optimise the propulsive characteristics of a crew.
- 5 The signals gathered by using the devised data acquisition system could be used to design rowing shells meeting the specific requirements of a crew, allowing the athletes to more easily optimise their on water performance.

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