High Performance Rowing
A Research Outlook using a Coaches Perspective

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Abstract: The purpose of this paper is to explore research opportunities in the Olympic sport of rowing. While innovation in equipment is promoted in rowing the FISA rules don't allow for it to be a deciding factor in the performance outcome for an individual crew. Thus, the challenge is to look at innovative ways to develop these abilities within a boat and harness their energy to create the most efficient and effective machine. This paper describes an outlook identifying four areas containing research opportunities with an emphasis on being able to 'fine tune' the moving parts of the engine that is a rowing crew: Sonification in the learning of motoric movement, rowing dynamics that will impact the hydrodynamics around the hull by inducing pitch and heave instead of forward propulsion, surface structures and finally objectivity in on water performance. A research outlook is made into different research opportunities in Rowing, using a coaches perspective. Another novelty is the comparison of the work carried out by the athletes in the rowing to the situation in production systems with assembly operators working at assembly workstations, opening up an new area of well-established theories to by utilised in sports.

1 INTRODUCTION

The Olympic motto, *"Citius, Altius, Fortius"* (Latin for "Faster, Higher, Stronger"), governs everyday life for many engineers. During the past few years, Chalmers has supported a project that focuses on the possibilities and challenges for research combined with engineering knowledge in the area of sports. The initiative has generated external funding and gained great acclaim within Chalmers, among staff and students, in the Swedish sports movement, and in large companies as well as within small and medium size enterprises (SMEs). The project focused on five sports: swimming, equestrian events, floorball, athletics, and sailing. But of late, an expansion into further sports have starter. This paper divulges into the Olympic sport of Rowing.

The world governing body for rowing, FISA, is the oldest International Sport Federation, created in 1892, rowing has been on the Olympic program from the beginning in 1896 and has 142 member federations in all five continents. While innovation in equipment is promoted in rowing the FISA rules (FISA, 2013) don't allow for it to be a deciding factor in the performance outcome for an individual crew. Rule 40: Innovation in equipment including, but not limited to boats, oars, related equipment and clothing, must meet the following requirements before being used in the sport of rowing: Firstly, be commercially available to all competitors'. Secondly the factor deciding the outcome of rowing are the physiological and technique ability of individual athletes. Thus, the challenge is to look at innovative ways to develop these abilities within a boat and harness their energy to create the most efficient and effective machine. Like the engine of a car, the individual moving parts need to work to maximum efficiency as both independent units and together as a crew.

A research outlook is made into different research opportunities in Rowing, using a coaches perspective, as one of the authors is an Olympic level international rowing coach and a previous world-class athlete in rowing. With this in regard, this paper will contribute towards coaching tools to improve and increase efficiency of the coaching process and to maximise the effectiveness of training hours of rowing crews, without an increase of

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training hours per session or requiring additional staff. Another novelty is the comparison of the work carried out by the athletes in the rowing to the situation in production systems with assembly operators working at assembly workstations, opening up an new area of well-established theories to by utilised in sports.

1.1 Research Challenges in Olympic Rowing

Rowing is a sport that requires a number of sequenced movements repeated efficiently in repetition. From the coaches perspective, the movement itself is quiet simple yet to maximize the efficiency of this sequence takes a lifetime. Rowing has proved over the past 6 years that proper talent identification programs, actively seeking athletes fitting a particular physical and anatomical requirement will (under the right conditions) produce world and Olympic champions in a relatively short time. The challenge then is, once having found the 'right engines' how to teach them in the most effective way the proper movements based on objective data. The fine tuning of an engine to maximize the use of the power being created. If a crew is to experience 'flow' by achieving perfect timing and we have the data points to measure against that give athletes Harmonic and auditory feedback, then the process of flow becomes more like tuning an instrument in real time.

From that point then ability to get these individual engines to work in near perfect synchronization working with an objective on water system. A tool that would assist further advances in boat and equipment design as well as objective crew and boat selection.

However, none of the above is in any way simple, and the tactile knowledge acquired during coaching at the international level, can be simplified or combined with contributions from science. Questions that arise from the above indicate that the movements from the rowing crews need to be synchronized to accommodate for individual crew properties impacting the performance of the boat. This indicate that there is a need to further investigate both how to achieve a better synchronization, as well as generating knowledge on how the synchronization affects the performance of the boat, the rowing dynamics.

And in approaching the performance of the boat and how the boat itself is moving through the water, the issue of hydrodynamics and the properties of the boat itself is obviously important. Even so in considering the constraints provided above in all innovations being available to all competitors, from a research point of view in improving performance, the surface structure of the hull is of importance.

Moving from inside or the vicinity of the crew and boat, the nature of rowing as a sport, in particular it being an outdoor sport, means results produced on water are difficult to objectively monitor. Factors including wind, tide, water temperature and water density greatly affect the outcome in terms of performance from an individual boat and crew, as well as all boats in a competition. All affecting crews and a coaches ability to make objective decisions based on performance in any particular race or training session. The need for objective on water monitoring would allow for better control of performance, and for better testing of materials boat and oar design and ultimately crew selection.

1.2 Purpose of the Paper

From the above background and described problems, the purpose of this paper is to explore research opportunities in the Olympic sport of rowing.

1.3 Methodology

This paper is a development of an on-going discussion between the rowing coach and the centre of sports technology at Chalmers, with this paper as a joint and equal effort by the authors. From the discussions using the coaches perspective, several research opportunities have been identified, and thus a selection of them are included in this paper. The problems have been selected on the basis of their challenges and connection to theoretical knowledge from literature, the coaches perspective on the practical relevance for the sport of rowing, as well as the possibility to do research within the suggested avenues of research.

1.4 Outline of the Paper

The paper describes an outlook identifying researchable problems related to high-performance Olympic rowing. The paper is divided according to four directions proposed for further research. Section 2 covers sonification in the learning of motoric movement and Section 3 how the rowing dynamics are affecting the performance of the rowing boat. Section 4 addresses surface structures. Section 5 progresses into the objectivity in on water performance for rowing. Finally, Section 6 will summarise the contributions made in the paper.

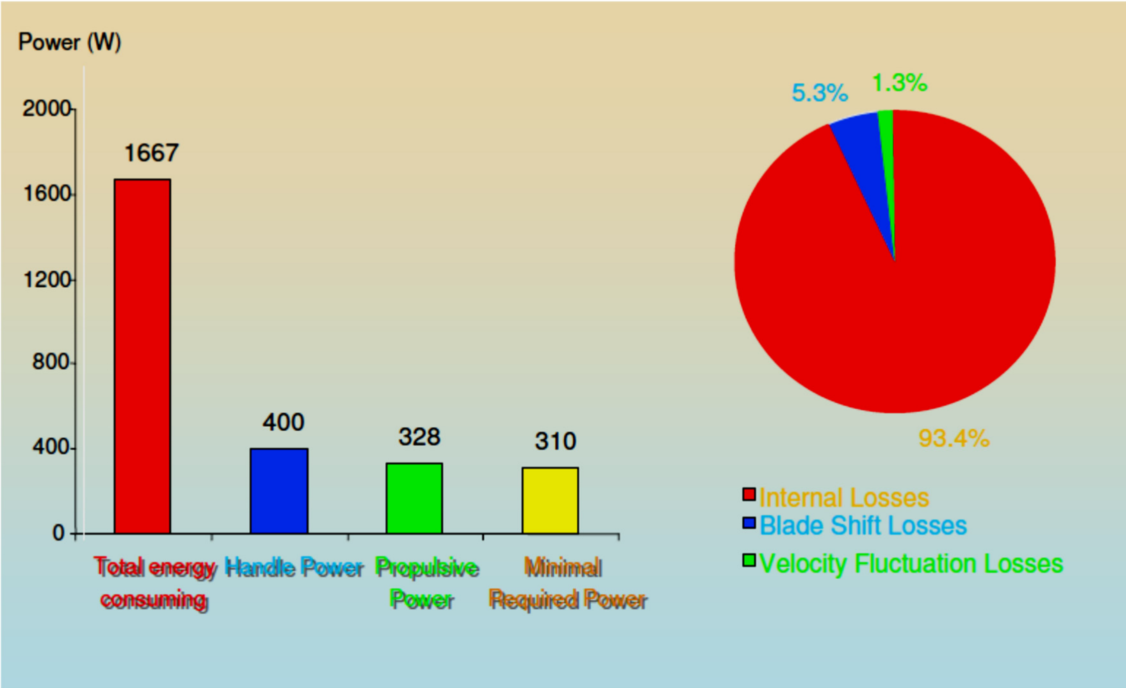


Figure 1: Energy losses in rowing.

2 SONIFICATION IN THE AID OF MOTORIC AND SEQUENCED MOVEMENTS FOR ROWING

The sequence of the rowing stroke creates an ideal activity for work in the areas of improved learning methods in particular sequence and motoric movement. In addition there is the need and desire for near perfect synchronisation of these movements in a crew boat (up to 8 people). The sequence timing and synchronisation of both crew and individual can be objectively identified however the means in which it is transmitted to coach or athlete is too fast (direct visual feedback) or too slow (post session feedback). Inter athlete synchronisation in relation to a changing rhythm within the boat.

Sonification as an aid for learning motoric movements and sequence movements in rowing is an area of research area yet to be explored. On a larger scale, sonification in rowing is an emerging area of study, with a focus on boat acceleration as well as the use of sonification in recovering stroke victims the potential of auditory feedback in rehabilitation systems is largely underestimated in the current literature (Molier et al., 2011). Maulucci et al. (2001) used audio feedback to inform stroke subjects on the deviation of their hand from the ideal motion path and found that the auditory feedback training improved performance.

In coaching rowing the importance of correct sequence is important in the ability for an athlete to make efficient stroke (refer to Figure 1 for a summary of energy losses). 83.2% of metabolic energy consumed by rower is wasted. From this amount the majority of the energy losses, 77.2%, occurs inside the rowers body. Blade slippage contributes merely 4.9%, and boat speed variation only 1.1% to the overall energy loss. (Nolte, 2011). High-performance rowers use ideal movement paths for the effectiveness of their recovery which directly relates to the speed and efficiency in the boat; The use of body sequence and hand pathway data to increase boat speed has increased with the availability of technology measuring these points. Traditional feedback works through the coach and the delay time could be from minutes or hours up to days or weeks. Immediate feedback presents information to an athlete and delay time is in a range of seconds. More sophisticated methods employ computerized telemetry systems, which acquire biomechanical data, process it and deliver it to the athletes eyes in real time (display of data and/or video pictures on mini-monitor). An important part of this method is a clear understanding by the athlete of the information being provided. This must be done in conjunction with a coach and based on traditional methods of feedback.

Acoustic representation of the processed biomechanical data in the feedback-synthesis phase of sport science and biomechanics can allow a much less time consuming process of both coaching and understanding of the data being measured.

Yet the traditional visual feedback in which this information is used by coaches and athletes creates a too fast (in the case of direct visual feedback) or too slow (in the case of post training de brief) information to maximize the data available. Harmonic and auditory feedback for direct athlete feedback in the learning of motion and sequence are of special interest for further research and theory, as well as in practice for high level teams.

The fine details of the pathway movement and sequence of the stroke cycle contain a number of research areas with a multitude of academic and practical interests. Rowing provides an activity that requires repetition of a number of movements in sequence

As in most sports, the rowing movement has an optimal sequence pathway resulting in a higher speed outcome.

Contributions made in the area effective sequence learning in rowing, by the use of harmonic and auditory feedback can be translated into increased knowledge into injury prevention, Concurrent feedback for enhance learning of complex motor tasks and methods of improved correlation.

3 ROWING DYNAMICS

The dynamics of a rowing boat is a research area yet to be explored. On a larger scale, ship propulsion in waves is an emerging area of study, with a focus on energy consumption. The analogy to rowing in smaller boats differs, as high-performance rowing boats use a large proportion of the mass of the boat and crew for their propulsion. The induced flows around the boat are of special interest for further research and theory, as well as in practice for rowers. The propulsion can be both muscularly induced and/or induced by bodily movement, thereby presenting an array of scientific challenges, especially in how the boat moves in x- and y-axis's as a result of the strokes and bodily movements. As means to reduce these movements, synchronisation inter-crew can be used to align the propulsion force and reduce x- and y-axis's movements.

The physics of rowing contain a number of research areas with a multitude of academic and practical interests. They can be compared to sailing, but differing from sailing in that sailing use aerodynamics as the main propulsion force. Below follows a small compassion between a sailing yacht and a rowing boat. As all surface vessels, a sailing yacht travels in the intersection between two media. Its difference from, for instance, a cargo ship is that the two media are of equal importance. Aerodynamic forces cause propulsion, while the resistance that it is to surpass is decided by the hydrodynamics of the underwater shape. For most ships, aerodynamics is of little importance, and compared to rowing the situation differs in that rowing as stated above use the force from the crew as the only propulsion force.

Especially interesting are the physics of sailing yachts in waves, which presents a very dynamic problem. The hull must be propelled optimally in the wave in both head and following seas. The aerodynamics is complicated by the often sudden movements of the mast, whereas in rowing these sudden, but very repetitive, movements are made by the crew.

Little research is available about sailing dynamics and somewhat more about rowing dynamics (such as for instance in Clanet, 2013). We estimate that current research efforts in this area will contribute to exploring and explaining recent developments in high-level performance in today's Olympic sailing and rowing, in which athletes' fitness and strength are evolving due to the dynamic parts of sailing and rowing. Academic endeavours in this area will be appreciated, by athletes and coaches, who will become able to adopt a more sustainable way of sailing and rowing boats closer to their performance potential. For a more in-depth discussions on sailing dynamics refer to Lindstrand et al. (2014) or Finnsgård et al., (2015). The approach to study an Olympic class sailing dinghy in a towing tank deviates from previous research, that for instance focus on method development (Day and Nixon, 2014) or accuracy and repeatability of tank testing (Ottosson et al., 2002 or Brown et al., 2002) using America's cup Class Yachts.

For the area of sailing and rowing dynamics, computational methods used until now are based on the potential flow theory that neglects viscosity. This approach provides adequate results for some movements, while inadequate and generally poor results in others. The increased resistance in waves is an area in which potential flow can be used for approximations only. As aforementioned, for newly constructed vessels, international regulations will necessitate accurate predictions of vessel resistance in waves. By using emerging computational capabilities, it is now possible to use the Reynolds-Averaged Navier–Stokes (RANS) type to use to simulate movements in waves in viscous flows. Contributions made in the area concerning sailing yachts and rowing boats, by the use of advanced RANS methodologies, can be translated into increased knowledge about the movements of ships in waves.

Ways of increasing the synchronisation between individuals in a crew boat can be further explored, near perfect timing between athletes in Olympic classes is a necessity in optimising performance. In rowing a chain connects the power applied by the athlete to the oar and then to the boat in order to propel. Energy moves through these three points. In coaching terms this is referred to the "efficiency" of the rower. This is measured as the ratio of the total mechanical power applied at the handle and the stretcher (Kleshnev, 2000) to the consumed metabolic power which can be evaluated using physiological gas-analaysis methods. This efficiency was measured at 22.8+- 2.2% (mean+- SD) (Fukunaga et al., 1986) Ergo (rowing machine) scores explain only 40% to 84% of variation in on-water performance in small boats and 10% to 50% in big boats (Mikulic et al., 2009) the rest is explained by other factors, including technique, crew synchronization, physiology and so on. Rowers with equal ergo scores can perform with a 10-15 seconds difference on the water, and winners and losers are often split by a fraction of a second. Synchronising the energy from the three points between up to 8 athletes is done through experience gathered in the individual athletes and input from coach and bio mechanic equipment.

In assisting a team to achieve maximum synchronisation 12 key moments in the cycle are defined. (Kleshnev, 2014) and then displayed in Figure 2, and shown with video in Figure 3:

***T1.* Min. Seat Velocity** (negative) during recovery, when switching from pulling to pushing the stretcher.

***T2.* Catch** – Zero handle velocity, when the oar movement changes direction;

***T3.* Zero Seat Velocity** at the catch, when the seat changes direction;

***T4.* Zero Vertical Angle** at the catch, when centre of the blade crosses water level

***T5.* Entry Force** 200N at catch (sum of left and right forces in sculling). The threshold was chosen to distinguish force in the water from oar inertia force.

***T6.* Force up to 70%,** which indicates engagement of large muscle groups.

***T7.* Max. Seat Velocity** during the drive, which indicates acceleration of rower's mass.

***T8.* Peak Force** – emphasis of efforts.

***T9.* Force down below 70%** shows maintenance of the force during the second half of the drive.

***T10.* Zero Vertical Angle** at the finish shows "washing out" of the blade.

***T11.* Exit force** 100N (sum in sculling) at the finish.

***T12.* Finish** – Zero handle velocity.

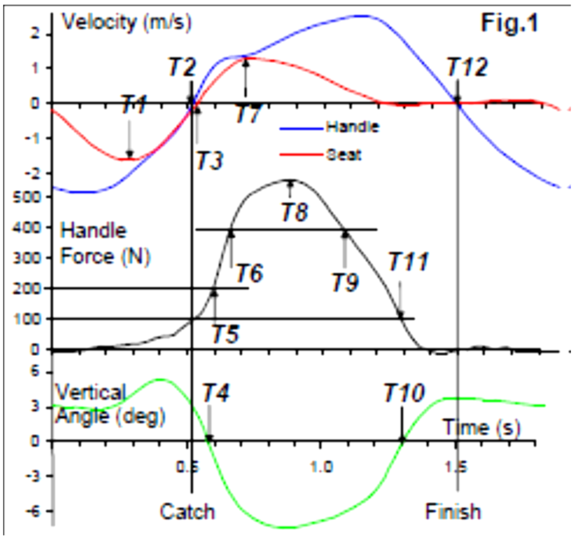


Figure 2: 12 Key moments in a rowing stroke cycle.

These points when perfected will generate a faster crew. The problem is the process is slowed down by the current limitations of direct athlete feedback.

The current system of visual feedback requires post session debriefing, trial and error then more testing to see if there was progress in a positive direction. It is a similar process to tuning a guitar without sound, being directed by a third party to tighten or loosen the string. By using harmonic and or auditory feedback the athlete would be tuning their 'instrument' together in real time which would add the advantage of real time trial and error in a split second of movement.

Another aspect of rowing dynamics is how the individual athletes working together for the propulsion of the boat. Albeit working individually, their individual position inside the boat is predetermined by the design of the boat. This will imply that their individual efforts will be connected into the same system that creates the propulsion for the boat. Alas there will also be losses in the transferal of the individual athlete's efforts, as explained in previous parts of the paper. Also on the entire system level (the boat) there are losses evident, in how the dynamics of two or more

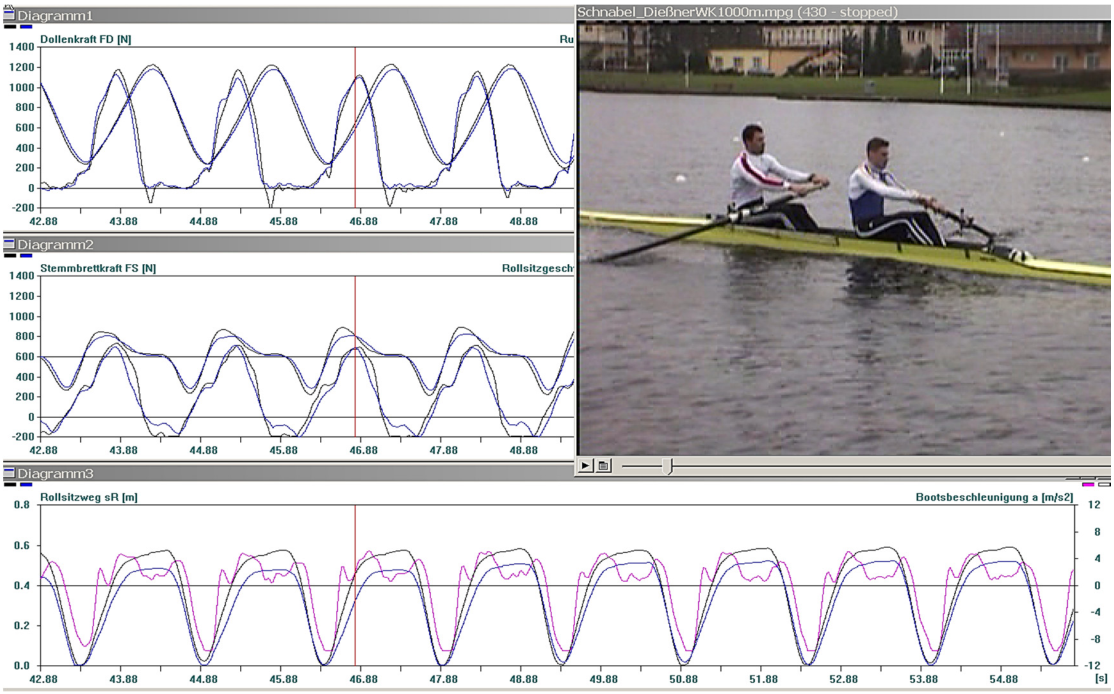


Figure 3: An example of synchronisation of video and biomechanical feedback.

athletes might interfere with another. By this stage, there are a lot of analogies with theories about production systems in industry. Since the area of production systems is very well researched since long, and in-depth, these analogies could be used for the benefit for the sport of rowing. Thusly, this section will endeavor into how to compare the synchronization of a rowing crew with a production system and a series of assembly workstations in an assembly system. A few general concepts will be discussed briefly and how they can be connected to rowing dynamics. It should be noted that this area could be further explored in all capacities with further research.

For a production system, efficiency is the internal performance of the studied entity. Effectiveness is the performance in relation to the environment of the studied entity (Öjmertz, 1998). For the situation of rowing this transfers to efficiency being how well the crew perform in relation to the specified targets for a race or training session, and effectiveness transfers to how well the entire crew and boat perform in relation to other boats in a race. Monden (1998) presents several performance measures more closely related to the workstation. The first objective, in establishing performance, should be to determine the *takt time*.

$$\text{Takt time} = \frac{\text{Regular operating hours}}{\text{Salable quantity of products}}$$

The takt time determines how much time is available to produce one product in relation to the available time frame, also considering the customer's requirements (Monden, 1998). One can certainly argue that takt time is not a performance measure as it has little to do with operations at the workstation, but it is important in itself as it links customer demand and output from the workstation. Takt time is also used as a way to establish requirements on other performance parameters (i.e. effects). The concept of takt time will become evident in rowing in how to synchronise the crew's individual efforts into the desired output, the takt. If the entire crew would work to a desired takt, the most likely outcome would be to win a race by a small margin, or another agreed target, translated into each individual stoke of the crew. However, determining. And if the concept of takt is used, the relation to section 5 in this paper will become evident.

Another interesting comparision between production systems and rowing can be done using the cycle time. The *cycle time* is explained by Monden (1998) as:

Cycle time = Total time necessary for performing the processes included in the standard (including non-value adding time).

Like takt time, cycle time is a term that is not mainly used itself for performance measures, but in describing other performance measures. For rowing, the cycle time would be the time for each rower's stroke.

The assembly line is a term that has been used in force in production systems for more than a decade. Usually the term is attributed to Ford (1926), but the use goes back further and any mentioning of the development of production systems should include the term scientific management as described by Taylor (1911). With the development of assembly lines and a layout following the flow of completion of the assembled product, the work tasks where divided into separated workstations performing different operations.

At the assembly workstation, being part of a flow or line, the distribution of operations between the workstations is termed *line balancing* (Wild, 1995). The time to perform the allocated operations at one workstation is called the *service time*. Note that the service time is from the workstation point-of-view, and not from a flow perspective. Combining service time and cycle time, three situations emerge: the cycle time is longer than the service time, the cycle time is equal to the service time, or the cycle time is shorter than the service time. For the two first two the operator has time to finish assembly; but in the last case, the operator will not finish assembly in time – this is thus a possible cause of disturbances in the assembly system (Ellegård et al., 1992; Monden, 1998; Wild, 1995). In any case, a difference in cycle and service time causes a *balancing loss* (Wild, 1995), refer to figure 4 for a depiction of theses terms. There is a very clear distinction between cycle time and service time to the takt time, as the two first are connected to the design of the workstation operations and the latter to the customer demand for the output of the production system.

For rowing this is somewhat intriguing. For the line balancing you have the different work tasks divided between what side of the boat the oar is on, and with the position in the boat determining who will set the cycle time (i.e. the time it should take to perform one stroke). If this time deviates in any rower's individual service time, a balancing loss will occur in the system as a whole.

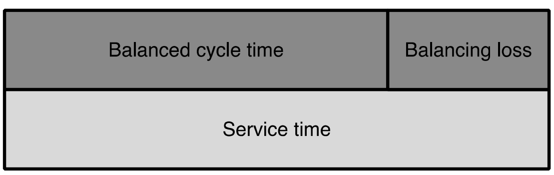


Figure 4: The principles of balancing losses (adapted from Ellegård, et al., 1992).

On balancing losses and cycle time, figure 5 provides some interesting results, based on the case studies by Wild (1975, 1995), as the balancing losses decrease with longer cycle time.

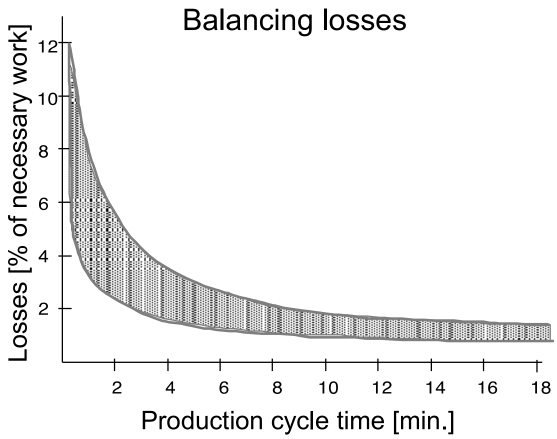


Figure 5: Balancing losses (%) vs. cycle time at the workstation (Wild, 1975, 1995).

Ideally, this means that it should be easy to design perfect assembly lines with matching service and takt times. However, this is difficult in practice because of differences, in the cycle time used, both between operators and in the same operator, as shown in figure 6 below (Wild, 1995). For rowing to use these results, there are several challenges, as the study does not divulge into the very short cycle times used in rowing. However the results indicate that balancing losses of between 4-12% or more are to be expected for rowing. Note that this is only the case of a crew of two or more. For the single sculler this is not applicable.

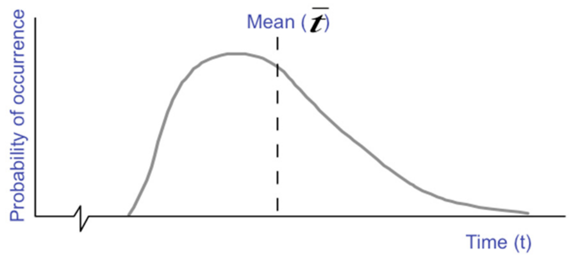


Figure 6: Time distribution for repetitive manual work (Wild, 1995).

With the variation in time, when the cycle time is less than the service time, a loss will occur, designated a system loss (Ellegård, et al., 1992; Wild, 1995). If several workstations are connected to each other in an assembly process, the relation between these is likely to influence system losses (Wild, 1975). As the variation in manual operations is very evident in a rowing boat, these results are very usable in rowing. Wild (1995) has shown how system losses can be reduced significantly by the use of buffers between workstations, see figure 7. Alas this is not applicable to rowing as all operations are performed simultaneously and a buffer is not possible to introduce, however tempting.

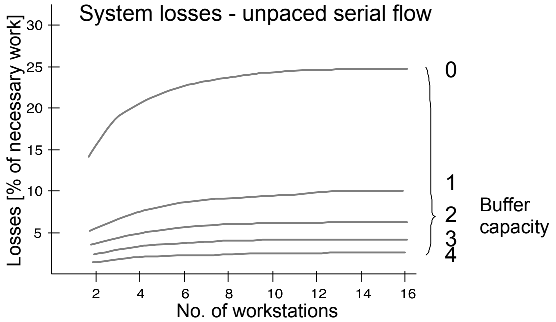


Figure 7: System losses (%) for different buffer capacities in un-paced serial flow (Wild, 1975, 1995).

These discussions how to view the operations inside rowing using the taxonomy form production systems have a very interesting potential. Apart from indicating the same set of problems, a very extensive set of toolboxes are available from previous research how to reduce losses in production systems. Applying these in the sport of rowing would be the next step in further research.

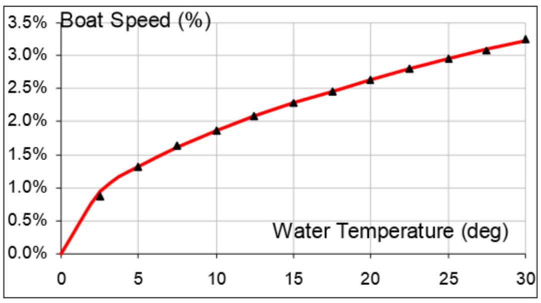


Figure 8: Dependence of the boat speed on water temperature. Points – experimental data of Klaus Filter, line – fitted power trend.

4 SURFACE STRUCTURES

Ways of reducing the resistance of ships is a very well-researched area, with current on-going research (refer to for instance Larsson and Raven, 2010). For rowing boats this area can be further explored, and special considerations for the high performance in Olympic rowing is a necessity. Surface structures offer an opportunity for research in this area.

However, the FISA rules (FISA, 2013) includes section 4.1, stating: “No substances or structures (including riblets) capable of modifying the natural properties of water or of the boundary layer of the hull/water interface shall be used“. Thus, working with surface structures in the sport of rowing encounters special considerations.

It has been known for some time, Bechert and Hoppe (1985), that the texture of the shark skin reduces drag. This has been exploited in several applications, the Speedo swim suit being perhaps the most well-known example. 3M developed a special film with longitudinal grooves, called riblets, used in the America’s Cup in sailing in the 1980’s. One of the involved researchers at Chalmers, Prof. Lars Larsson (and co-workers), patented a surface texture which had both drag reduction and anti-fouling properties, Berntsson et al. (2000). For a recent review of drag reduction using riblets, see Dean and Bhushan (2010). The possibility of testing these concepts in high-performance rowing would be an interesting avenue of research, to validate previous findings and explore the possibility of adapting the concepts and overcome the manufacturing aspects encountered in sailing as mentioned in Larsson et al. (2014).

5 OBJECTIVE WAYS OF MONITORING ON WATER PERFORMANCE

When it comes to the Olympic motto *"Citius. Altius. Fortius"* yes it does mean Faster. Higher. Stronger. But it doesn't mean faster, higher and stronger than who you are competing against, it just means faster, higher, stronger.

In rowing as in all sports, coaches seek objective date in order to work towards a set pathway. Monitoring of results in all aspects from the athletes anatomy and oxygen uptake through to gain in muscle strength and speed is recorded so a clear pathway is defined for the athlete or team. Objectivity in outdoor conditions is an obstacle that has limited a major part of the monitoring of progress in many Olympic sports. In particular rowing.

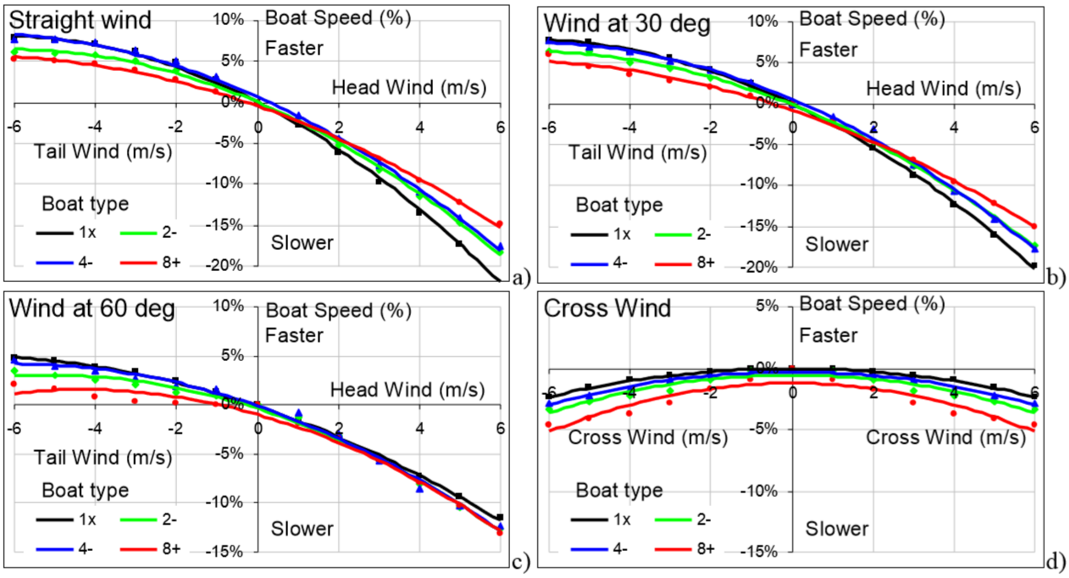
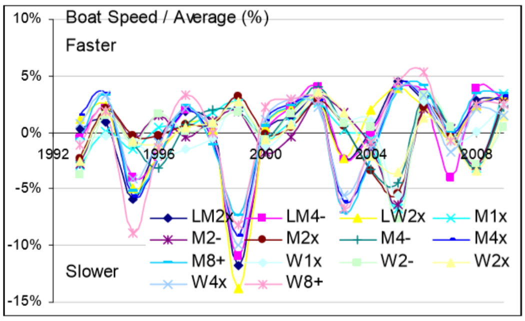


Figure 9: Dependence of the speed of various boat types on wind direction and speed. Points – experimental data of Klaus Filter, lines – fitted second order polynomial trends.



Boat	Min	Max	Range
LW2x	-13.8%	3.9%	17.8%
LM2x	-11.8%	4.5%	16.3%
LM4-	-10.9%	4.1%	15.0%
W8+	-8.8%	5.3%	14.2%
W4x	-9.9%	3.9%	13.9%
M4x	-9.2%	4.2%	13.4%
M8+	-7.3%	4.1%	11.4%
W2-	-7.7%	3.5%	11.2%
M1x	-6.8%	3.4%	10.2%
M2-	-6.4%	3.1%	9.6%
W1x	-5.5%	3.5%	9.0%
M2x	-5.5%	3.2%	8.6%
M4-	-4.5%	4.0%	8.5%
W2x	-3.6%	3.5%	7.1%
All boats	**-8.0%**	**3.9%**	**11.9%**

Figure 10: Variation of the boat speed relative the average in the boat type in the winners of World Championships and Olympic Games during 1993-2009.

With conditions such as wind, water temperature playing such a major factor in the finishing time of a boat, objectivity in any "on water" performance has been a task yet unattainable in rowing (see Figure 8 and 9). This has a significant impact for materials tested and for boat, oars and crew selection.

Due to its outdoor nature rowing has no "world records" (refer to Figure 10).

World's best times are used when a boat travels faster than any crew in history. This is due to many factors including water temperatures wind conditions, water density. As a result it is very difficult to objectively identify the speed improvement of a boat on water. In a local environment on a daily basis directional chances in wind and over longer periods change in water temperature influences the effect on absolute boat speed.

The problem in weather conditions on speed can be shown by the 2012 London games where the winner (Great Brittan) won the Olympic Gold in a time of 06:03.970.

While 6 weeks earlier the exact same crew (much less tapered and less race trained) won the second world cup in a world's best time of 05:37.860

That close to 8% in boat speed change. Refer to table 1 for a comparison. (note that the difference between 1st and 6th in both races was less than 3%).

Table 1: An example speed variation in one crew due to outdoor conditions.

English m4-	Time	[W]/500 m	Prognostic Time
World cup 2	05:37.860	580.81	102,11%
Olympic Games	06:03.970	464.57	94.97%

Environmental performance has been studied by for instance Pezzolli et al. (2015) in cycling regarding the effect the environment has on performance. An adaptation of this for use in the sport of rowing is highly interesting. Pezzoli et al. (2013) analysed a few factors regarding the impact of wind-wave interactions in enclosed basins (the case of rowing is an example of this).

While this paper suggests an adaption of these ideas would be to produce a pace drone is a boat that produces a particular speed through energy production. Its output of power is set and its speed is influenced by the same factors affecting the boat it paces.

For example in flat conditions with the water temperature of 20 (deg. C) the drone produces 420 W to travel 2000 m in 6:00 minutes. The drone is then placed in a different environment with a water temperature of 10 (deg. C) and a strong head wind. The drone is producing the same 420 W however its time after 2000 m (6:30) is 30 seconds slower. This is the challenge in objectifying a crews performance who train on different stretches of water at different times of the year and day. By being able to objectify a performance a crew will know that by being faster than their drone opponent they are in fact faster objectively. This can also open new possibilities to identify a crews strength and weaknesses in different conditions as well as assist in objective crew and boat selection.

In addition to this the drone could "mirror" the race profile of a boat in different conditions replicating the exact race plan in W regardless of conditions. The race profile from the opening speed out of the start (520 W) to the middle (480 W) would give crews the ability to gage themselves in race work creating an objective tool for coaches to monitor on water performance.

With current GPS data in rowing (and other sports) the potential to use the race profile from past international races enables crews to chase down a world or Olympic champion over the cause of season.

6 CONCLUSIONS

This paper has presented a multitude of research challenges related to high-performance rowing. Rowing provides the practical problem motivation for these research areas. As being a part of Chalmers' initiative into sports, several professorships have been suggested related to the issues raised in this paper. All providing excellent research opportunities and prerequisites for excellent world-class research within their respective fields.

The paper outlined three major issues in the sport of rowing, synchronisation (including several aspects entwined), rowing dynamics (including synchronisation and hydrodynamics), and the issue of objectively measuring performance of crews. Neither has been solved in this paper but research directions have been outlined and indicated.

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