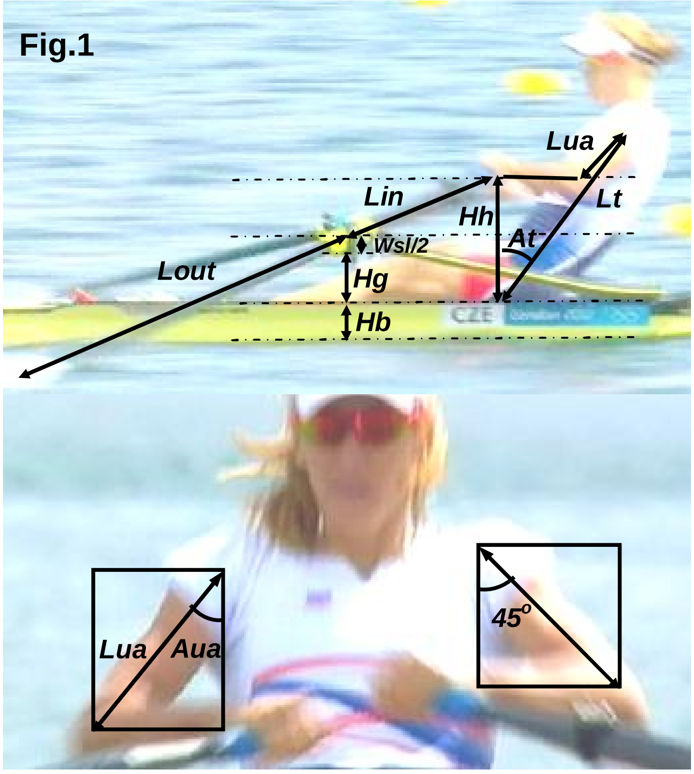
Rigging: Gate Height

We have already discussed some relationships between the gate height and the seat force (RBN 2002/05), blade pitch (2010/09), vertical angles (2009/10) and its specifics in sculling (2011/07). Now it is analysed directly and in more detail.

At the catch, a rower has much more freedom to vary the height of the handle pull, because the arm is straight. Therefore, the height of the handle and related gate height is mainly defined by position at the finish.

The simplest method to define the correct height is an empirical one: sit in the boat at the finish position, bury the blades into the water and find the most comfortable height for you. However, an analysis and normative values could be useful to predict the correct height for a rower in various boats; for understanding of effective technique and identifying the reasons of errors. Fig.1 shows the analysis of the gate height of Olympic champion in W1x Mirka Knapkova, CZE.

Fig.1



The main requirement of the correct rower's position at the finish - horizontal forearms, i.e. the elbow and the handle must be at the same level. Only this position allows effective horizontal pull. The height of the handle ***Hh*** from the seat can be calculated as:

$$Hh = Lt\cos(At) - Lua\cos(Aua)\cos(At) \qquad (1)$$

Where ***Lt*** - length of the trunk from the seat to the centre of the shoulder joint, ***At*** – angle of the trunk from vertical, ***Lua*** – length of the upper arm between centres of the shoulder and elbow joints, ***Aua*** – angle of the upper arm from vertical, for which the optimal value appeared to be 45° to engage the biggest shoulder muscles: *Latissimus dorsi*, *Trapezius* and posterior part of *Deltoid* muscles. The optimal height of the gate from the seat ***Hg*** at the defined handle height ***Hh*** can be calculated as:

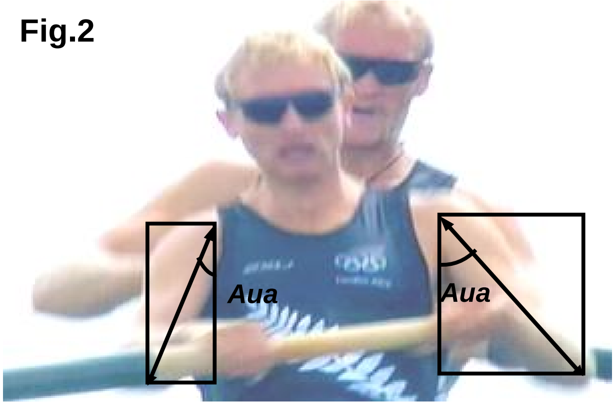
$$Hg=(Hh+Hb+\sin(-V)Lin)*Lout/(Lin+Lout)-Wsl/2-Hb=$$
$$Hh+\sin(-V)Lin)*Lout/(Lin+Lout)-Wsl/2-Hb(Lin/(Lin+Lout)) \quad (2)$$

Where ***Lout*** – length of actual outboard from the pin to the middle of the blade, ***Lin*** – actual length of the inboard from the pin to the middle of the handle, ***Wsl*** – width (thickness) of the sleeve, ***V*** – vertical angle of the oar relative to the water level, which should be below -3° for fully covered blade, ***Hb*** – height of the seat above water level. Though the model became quite complicated, it produces quite reasonable gate height ***Hg***=15.8cm at the following inputs: ***Lt***=50cm, ***At***=30deg, ***Lua***=25cm, ***Aua***=45deg, ***V***=-3deg, ***Lin***=84cm, ***Lout***=175.5cm, ***Wsl***=5.6cm, ***Hb***=10cm.

A large number of variables in the model allows endless combination of them: e.g. longer trunk leaning can be compensated by more horizontal position of upper arm, etc. Also, some variables itself are not fixed for the given rower: e.g. the length of the trunk ***Lt*** depends on the posture (how straight the torso is) and position of the shoulders (higher or lower *clavicle* and *scapula*).

The model works in sweep rowing as well (Fig.2), but upper arms usually have different angles: the inside arm has a more vertical position (elbow lower), because it produces a higher force at the finish.

Fig.2



The derived equations allow for the conclusions:

- Obviously, **<u>a higher seat position above water (in a larger boat) requires about three times smaller decrease in the gate height</u>**.
- **<u>Longer leaning with the trunk at finish requires lower height of the handle and gate and vice versa</u>**, because ***cos(At)*** decreases at larger angles. At the same other inputs above, the trunk angle 20° gives the gate height 17.5cm and trunk angle 10° – 18.5cm.
- **<u>The lighter the gearing, the lower the gate and vice versa,</u>** but the effect is quite small. At the same other inputs above, 10cm shorter outboard ***Lout*** would require only 0.5cm lower gate.
- **<u>The optimal gate height is important for effective blade work and force application at the finish of the drive</u>**. The gate being too high would increase finish slip of the blade ("washing out").

Vertical Handle Force

Last year, the first pilot study on the vertical oar forces was done with our ***BioRowTel*** system and now we will discuss the results. The vertical handle forces were measured with the same sensors as the horizontal forces, which were attached to the oar shaft at 90° to each other (Fig.1). These two sensors were positioned in two orthogonal planes and measured oar flex in horizontal and vertical directions.

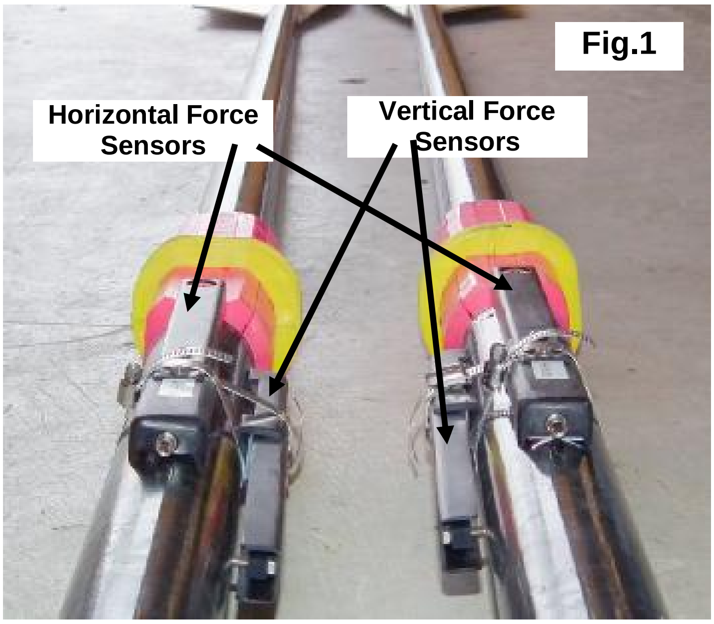


Fig.1

The data of the right oar of a single sculler at the stroke rate 36 str/min is shown on Fig.2.

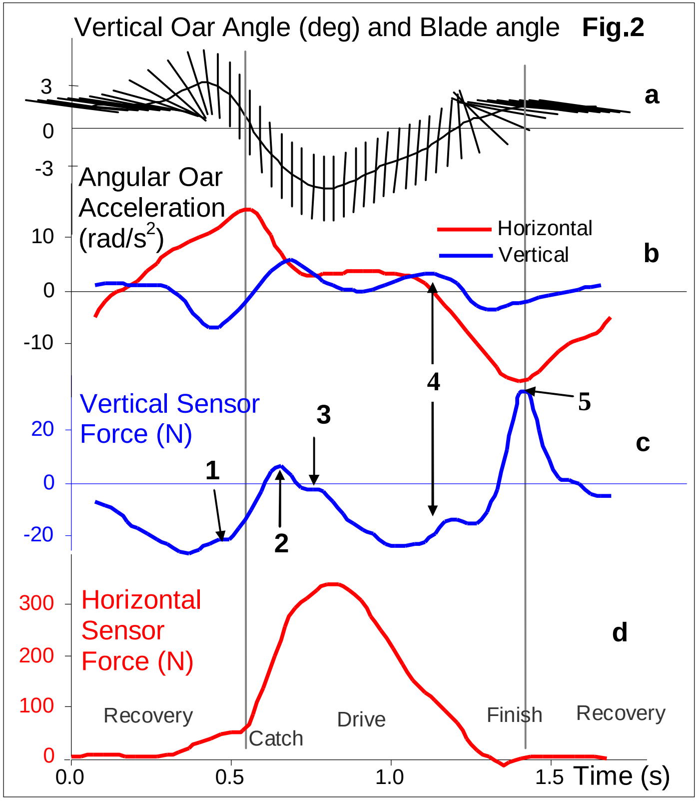


Fig.2

As the oar squared and feathered during the stroke cycle, the orientation of the sensors is changing relative to the horizon. Therefore, the oar roll was measured with ***BioRow*** 7D sensor (RBN 2012/10), so the orientation of the blade and sensors was determined (Fig.2, a). Angular oar accelerations (Fig.2, b) were derived by means of double differentiation of the oar angle in the horizontal and vertical planes, which were measured with ***BioRow*** 2D oar angle sensor. When the blade is in the air and the forces on it are negligible, the handle force ***Fh*** and angular oar acceleration ***a*** in each plane are related as follows:

$$Fh = I\,a / Lin.a \qquad (1)$$

where ***I*** is the moment of inertia of the oar relative to the pins centre of rotation, ***Lin.a*** is the actual in-board from the pin to the middle of the handle. In this study and previous in-lab measurements ***I*** was found to be 3.4-3.6 kg·m^2 for a scull and 6.6-7.0 kg·m^2 for a sweep oar.

Before the catch, when the blade is already squared, but still in the air (Fig.2, 1), the sculler applies about 20N (2kgF) of negative (upwards) vertical handle force to insert the blade in the water. When the blade enters the water, the vertical force became slightly positive (2), which means the rower pulls the handle slightly down to stop the blade going deeper. At the deepest blade position, the vertical force is very close to zero that means the pull is horizontal (3).

It is interesting that during the second half of the drive (4) the vertical handle force again has a negative value of about -20N, but vertical angular acceleration became positive. This means the rower pulls the handle slightly upwards and tries to keep the blade deeper, but it moves out of the water. This fact could be explained only by the upwards force at the blade, which is related to a positive pitch angle (+6°). At ~200N horizontal handle force it creates ~20N of vertical force (sin(6°)=0.1). At the finish (5) the blade is already feathered, so significant positive force measured by the sensor is related to the horizontal acceleration of the oar.

At higher stroke rates (Fig.3), the higher negative forces were measured during recovery (1) and at finish (2), which is explained by higher horizontal accelerations. The upwards kick of the handle before catch stays nearly the same (3), but positive blade force after the entry increases (4).

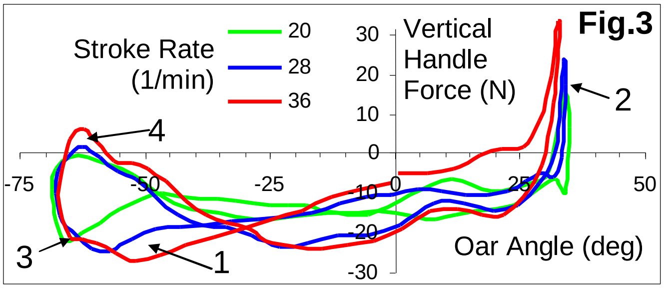


Fig.3

Concluding, **vertical forces at the handle are quite small and even smaller at the blade (about 10N ~ 1kgF), so they do not really contribute to vertical movements of the rower-boat system**.

A significant part of the handle force is directed vertically: from 7% at pitch 4° up to 14% at 8°.

Variable (lateral) pitch could be recommended to minimize vertical forces and make the blade path in the water more horizontal. (RBN 2010/09)

Biomechanical assessment procedure

An important part of the Biomechanics assessment procedure is the testing protocol, which must provide standard conditions and make results comparable between rowers and over the course of time. **There are two major factors affecting rowing technique: the stroke frequency and fatigue**. Therefore, historically, we used a test protocol consisting of two parts:

- Step test with increasing stroke rate: e.g. 5-6 pieces by 250m or 1 minute at 20, 24, 28, 32, 36 str/min with a free recovery about 3-5 minutes and 30 second maximal effort;
- Race piece 2000m with full effort or specified percentage of it (say, at 95%).

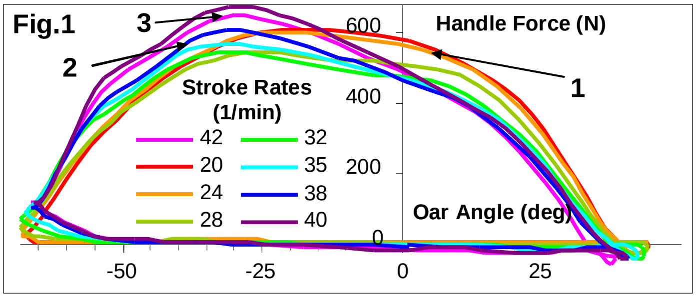
This test protocol takes quite a long time to complete (1-2 hours depending on recovery time between two parts) and puts a significant load on rowers. Therefore, last year we designed a combined test protocol, which allows determination of both effects at once. The test consists of one continuous 2000m piece at racing force application, but various rates (Table 1):

Table 1	**Split**	**Lap**	**Stroke rate (1/min)**	
Piece N	**(m)**	**(m)**	**Singles**	**Crew boats**
1	0 -100	100	Start max	Start max
2	100 - 500	400	18	20
3	500 - 1000	500	22	24
4	1000 - 1250	250	26	28
5	1250 - 1500	250	30	32
6	1500 - 1750	250	32 -34	34-36
7	1750 - 1900	150	35-36	38-40
8	1900 - 2000	100	Max.	Max.

The feedback from rowers and coaches was that this test is a good training load itself: the first half of it is performed at aerobic training intensity, which allows smooth transition to the second half with anaerobic intensity. Only the last 500m is performed with the stroke rates close to racing. There can be some variation of this protocol for junior rowers and veterans: e.g. the pieces N5 and 7 could be replaced with light paddling with corresponding reduction of the stroke rate for the next pieces. The data samples are taken and averaged at every lap (RBN 2012/12).

Fig.1 shows an example of changes in the force curve over the course of the test in a top level sculler.

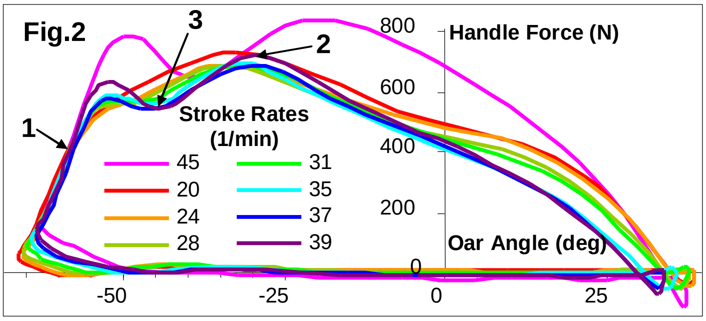
Fig.1



The specific feature of this sculler is a significant change in the timing of the maximal force application: at lower rates he applies more force at the second half of the drive (1), but at higher stroke rates the peak force is shifted to the first half of the drive (2). The comparison of the start and finish sections (3) gives us information about fatigue resistance, which was good.

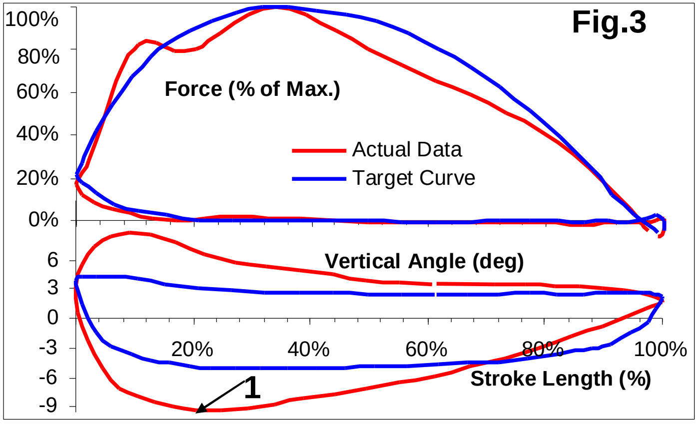
Fig.2 shows another example of changes of the force curve at various stroke rates in a National level sculler. The force gradient (rate the force increasing) at the beginning of the drive (1) remains the same at all stroke rates, as well as the position of the peak force (2). However, at stroke rates higher than 30 this sculler suffers from the 'hump' in the force curve (3), which is caused by early activation of the trunk at the catch, then a decrease in its velocity when the leg drive is the fastest. The hump occurs at the moment of the second activation of the trunk (RBN 2010/06) and is also related to a weak posture of the sculler (2010/02) and very deep burying of the blade (Fig.3, 1). Such "disconnection" and double emphasis of force application significantly decreases rowing effectiveness at racing stroke rates and negatively affects performance.

Fig.2



It is assumed that the conditions of the second last piece are very close to the racing conditions in terms of stroke rate and fatigue. Therefore, we usually take this data sample and compare it with "targets" to evaluate the technique of each rower (2007/08, 2011/10). The comparison is made in two ways. Qualitative values are compared with the main criteria and percentage of differences are defined for variables of oar angle (2001/11), force (2008/02), blade work (2009/10) and body segments (2002/02-3). Qualitative evaluation is made by means of comparison of the real measured curves with some hypothetical target curves (Fig.3), which were built on the basis of quantitative values.

Fig.3



Our method allows clear and effective feedback for rowers, coaches and helps improving technique.

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Vertical seat force

We already discussed the vertical seat force before (RBN 2002/05, 2011/03), but recently new data was obtained with a new design of ***BioRowTel*** instrumented seat (Fig.1) and will be discussed here.


Fig.1

Three lightweight single scullers of similar body weight performed a step test in the instrumented boat in similar tail wind weather conditions. Fig. 2 shows the comparison of the main biomechanical variables at the stroke rates 32.5 – 33.4 str/min, synchronised at the catch time (the longest oar angle).

The first sculler has shown the highest maximal handle force (1) – near 100% of his body weight, while other scullers achieved only 80-85% of it. The rowing power of sculler 1 was 15% higher than of sculler 2 and 12% higher than of sculler 3.

At the catch, only 40-50% of the rower's weight remains on the seat (2), which is explained by transfer of the weight to the stretcher. It was expected, that the weights will be lifted from the seat more and more together with force increasing. However, it does not always happen: sculler 1 increased his seat force up to 60% first (3), and then lifted it again. We could speculate that this phenomenon is related to a slow legs movement and slow growth of the handle force.

After the handle force increased up to 70% of its maximum, only 2-4% of the body weight was left on the seat (4). No significant difference in the minimal seat force was found between scullers, but sculler 3 with a faster legs and steeper force curve lifted his weight earlier.

During the second half of the drive the seat force is increasing and achieving 100% of the body weight, when the handle force drops down to about 20% of its maximum. Sculler 1 with a later peak of the trunk velocity maintained suspension longer, but then put his weight on the seat much quicker. At the finish, he achieved the maximal seat force of 150% of his body weight (5), while it was only 120% for sculler 3. This difference is also related to much faster trunk return at the beginning of recovery of sculler 1 (6).

As a result, sculler 1 had the amplitude of the boat pitch (Fig.2, h) was 2.2 deg and the vertical movement of the hull 4.2cm, while for sculler 3 they were only 1.6 deg and 2.5cm. Together with a more efficient boat acceleration profile (RBN 2012/11) and longer angles, it allows sculler 3 to achieve the same boat speed as sculler 1 at 12% lower average force and power. Sculler 2 achieved 4% lower boat speed at similar force and power to sculler 3.

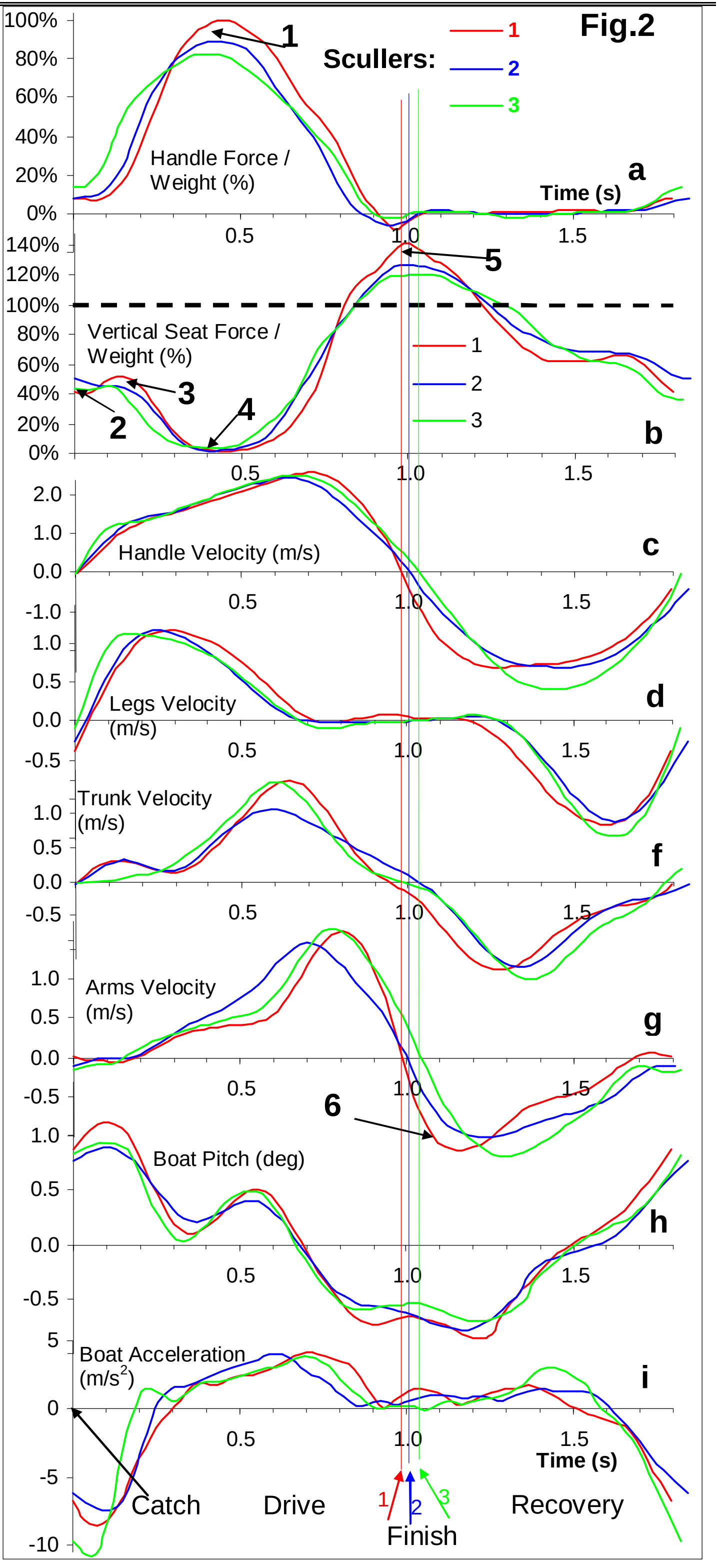


Fig.2

- **At the catch, up to 60% of the rower's weight is transferred onto the stretcher and only 40% is left of the seat.**
- **Fast and early legs movement allows achieving smoother weight suspension during the drive, lower amplitude of the pitch movement of the hull and higher rowing efficiency.**
- **Long and late trunk work at the drive and too fast return to recovery creates a significant increase of the seat pressure (up to 150% of rower's weight) and decrease rowing efficiency.**

Technical Exercises or Drills

The simplest way to improve technique is giving feedback to a rower during normal rowing or after it. However, technical exercises or “drills” appeared to be the most effective tool for technical coaching. When doing drills, the biomechanics of normal rowing is modified in such a way, which allows to focus on a specific part of the stroke cycle, emphasise it, make it easier or more difficult to do. We would classify a big variety of drills by the following three factors:

- Mechanics: static or dynamic drills.
- Level of details: for elements of sequences.
- Standard or modified mechanical conditions.

Static drills target rowing kinematics: positions, angles, etc. These are the most basic drills and usually beginners start with them: e.g., they stop at the catch position, see and feel where their handles, blades, body segments and hear coach’s comments on them. Then, they stop at finish, etc. Sequences could be trained with series of fixed positions and slow transitions between them.

Dynamic drills are more advanced and target rowing kinetics: pattern of force application (force curve), rhythm (pattern of velocity) of the stroke cycle or its elements (drive, recovery), optimal activation of muscle groups, etc. Examples of effective dynamic drills: 1) catch with short legs drive until knee angle 90^o - emphasise “kick” the stretcher through toes and knee extension using quads; 2) rowing half-slide, catch at knee angle 90^o with “kicking” the stretcher through the heels – emphasise pushing knee down and hips extension using hamstrings and gluts (RBN 2007/07).

Drills for elements are performed with focusing on one or a few elements of the stroke, which allows their more intensive improvement: e.g. catch only, finish with arms only, oar feathering-squaring, etc.

Drills for sequences target better coordination of elements: e.g., sequence of activation of legs, trunk and arms during the drive and recovery, sequence of the oar squaring and entry at catch, etc. A good example could be cyclic performing the Dynamics dill 1 above, say, for 3 strokes, then drill 2 for 3 strokes, then 3 strokes - combination of them with focusing fast switching between quads and hamstrings-gluts.

Drills can be performed at standard or modified **Mechanical Conditions**: e.g. external resistance can be increased with water brake or heavier gearing, or decreased with towing or lighter gearing, which makes rowing conditions heavier-slower or lighter-faster. The first sort of these drills is very often used for training of rower’s specific strength-power; the second sort is used sometimes for speed training (RBN 2004/05). Also, various gadgets can be used (RBN 2004/04, 2005/04), which restrict or modify mechanical conditions of rowing.

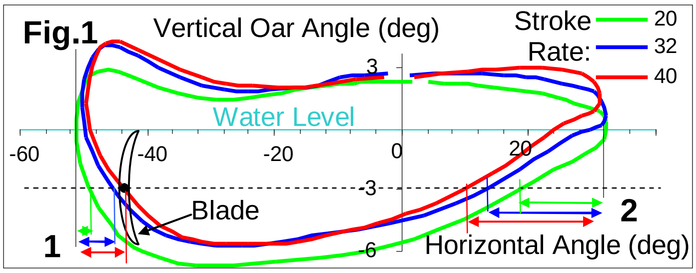
For quality coaching, it is important to have sufficient “toolbox” of drills, to choose a correct drill for a specific technical problem and fix it up in the most effective way. This is the “art” of coaching, which is based on a coach’s ability to see-identify-understand the problem and then to choose the most effective “treatment”. We will try to give some general rules and advice, which may help.

If your target is to win races and not rowing for recreation, you should **always refer technical drills to the racing speed and stroke rate**. Very often, “a technical session” means very slow rowing with stops and static drills. It could be good for teaching beginners, but at advanced level it is necessary to include also fast drills. There are a number of reasons for it:

1. Mechanical conditions are very different at slow and fast rowing, at low and high stroke rate: they are as different as walking and running. Inertia forces are negligible at slow rowing, but at high stroke rate they play a decisive role and change biomechanics dramatically. E.g.: when stroke rate is changing from 20 to 40 min^{-1}, rowing rhythm is changing from 35% to 55% (RBN 2012/05) and inertial losses increasing from 3% up to 7% (RBN 2010/05).
2. Mechanisms of motor control are different at low and high speed movement. At low speed, an athlete has enough time to receive immediate feedback (visual and from proprioceptors) about his body position, so he can control the movements and correct them in real time. At high speed, the quickness of the neuron-muscle loop is not sufficient to control movements at the conscious level, so its pattern should be programmed before the movement starts as it is not possible to control it in real time.
3. It is important to economise correct technique, i.e. perform it with the highest efficiency and proper muscles relaxation, which should be practised at racing stroke rate.

As an example, Fig.1 shows some very common profiles of blade work at stroke rates 20, 32 and 40 min^{-1}. The catch slip increases from 5^o at rate 20 up to 10^o at 40 (1) and release slip increases from 7^o up to 17^o (2). This happens because the vertical angular velocity remains the same, but horizontal velocity increases nearly twice at higher stroke rate.

Fig.1



If a rower targets improvement of blade work at racing speed, he needs either to increase vertical handle velocity proportionally at higher rates, or exaggerate it at lower rates. Both ways make sense and could be practised with drills “catch only” and “finish only”, when a quick short vertical movement of the handle is emphasised at various stroke rates.

Seat Racing and Crew Selection

Seat racing is quite a popular method of crews selection for big boats. How objective is the seat racing? This question is very important, because it may define an athlete's carrier. Here we will give some recommendations and outline common mistakes.

Example. A coach has firmly selected six rowers for an eight, and four other rowers bidding for two seats. Four 2000m races were performed, where four rowers were rotated on two seats and the ranking was made by the average time for a rower in all races. The boat was equipped with ***BioRowTel*** system, which measured the handle force, oar angles and other variables, and rowing power was derived (Table 1).

Table 1 Race N	Race Time	Rowers A–F	Rower G (W)	Rower H (W)	Rower I (W)	Rower J (W)
1	6:33.0	267.4	267.3	272.5		
2	6:33.7	253.1		259.1	284.8	
3	6:43.0	247.3			277.1	271.2
4	6:39.8	244.5	259.2			279.5
Average Time		6:36.4	6:36.4	6:33.3	6:38.3	6:41.4
Average Power		253.1	263.3	265.8	280.9	275.4

It was found that in the course of racing the average power of the six constant crew members (rowers A–F) gradually decreased by 22.9 W or 8.6%, which should decrease the boat speed by 2.7% or ~10s for above race times. The reason was quite obvious: the athletes got tired, so at the end of racing they were not able to apply the same power as in the first race. Therefore, rower H seeded for the first two races had the best average time 6:33.3 and rower J seeded for the last two races had the slowest average time 6:41.4, though his rowing power was higher (275.4W) than in rower H (265.8W). Without biomechanics, rower H would be selected unfairly. **Fair seat racing is not possible in one boat only. It should be done between two or more boats racing one against another**: the eight and pair or two fours in this example, so fatigue would affect all rowers similarly.

Another important factor to be considered at seat racing is weather conditions: wind speed and direction. It is very likely they could change in a few minutes between the races and severe affect the results. This strengthens above conclusion: **it is very important to measure performance in relative margins between two or more boats racing together, but not in the absolute times of a boat racing repetitively**. Also, it is always better to race with a tail wind, variation of which has much lower effect on the boat speed, then variation of the head wind (RBN 2009/12). The races in the example above were done in a head wind, which increases the uncertainty of results.

With a sensor placed directly on the boat canvas, ***BioRowTel*** system allows very accurate measurements of wind speed and direction (Fig.1). It makes possible to derive absolute speed, which could be shown by the crew at zero wind. Comparison of the absolute boat speeds in various pieces helps to evaluate rowing technique and precisely determine the effect of variations in a crew combination, rigging or rowing style.

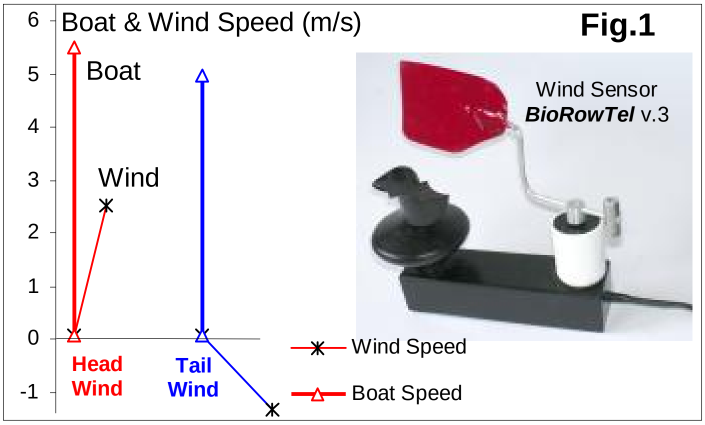


Fig.1

Though biomechnical measurements provide very useful information, we would discourage using them as a selection tool for two main reasons:

1. Even with the current selection of the most informative measured characteristics, we can not measure everything in a boat. There are another known and unknown variables and effects affecting performance and measurements: e.g., effect of power transfer through hull from one rower to another (RBN 2012/04). Also, there is a risk of occasional error.
2. We can measure only biomechanics and, partly, physiology of rowers. However, there are psychological factors, which may play decisive role at competitions. Some athletes are good performers at training and testing, but fade under the pressure. Others perform better and better, when psychological pressure increases with importance of a competition.

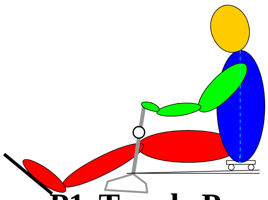
By the way, psychological factor may affect seat racing: rowers already selected for a crew, consciously or subconsciously, may perform better or worse on the basis of preference to a rower still bidding for a seat. This makes seat racing a sort of indirect voting for new team members. If it is undesirable, the selection should be announced for all rowers at the same time, so all of them must race full effort.

Objective selection for big boats must be done performance-based in standard races over 2km in small boats (singles and pairs). Power on ergometer could be taken into account, then seat racing could be used, if performance of two or more rowers is close or a rower doesn't fit well in the crew. After selection is made, the coach should adjust individual rowers' technique for the best performance in a crew. The purpose of Biomechanics is to help in this process, but not replace selection races. The factors affecting performance in a crew vs. small boats: synchronisation of movements of crew members and stroke timing (RBN 2011/02), coordination of force application to the handle and stretcher (2006/02, 2009/11), boat balance and asymmetry in sculling (2011/07).

BIOROW BIOMECHANICS OF ROWING **Rowing Biomechanics Newsletter** *No 148 2013 July*

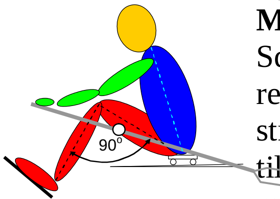
Stroke Cycle

The purpose of this article is twofold: 1) to describe our model of rowing technique; 2) to clarify definitions of rowing biomechanics terminology. The stroke cycle could be presented as 8 "Moments" M1-M8-momentary snapshots, and 8 "Phases" P1-P8 - transitions between the moments (Fig.1).



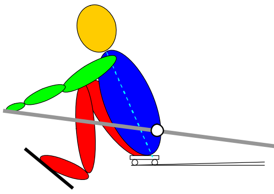
M1 Cycle Start. During recovery, the oar is perpendicular to the boat (zero oar angle). The handle is on top of the knees; the trunk is nearly vertical.

P1 Trunk Preparation. The trunk together with pelvis continues rotation ("pivoting") around hips, and the hamstrings and gluts are stretched. Knees gradually rise and the seat accelerates towards the stern. The rower smoothly pulls the stretcher according to the stroke rate (faster at higher rate).



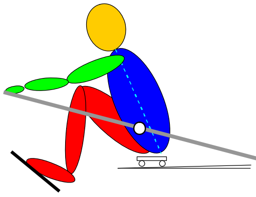
M2. Recovery Transition. Square (90°) knee angle during recovery. Handle on top of the stretcher. The trunk completed tilting forward to 25-30° and ready for the drive. Shoulders are low and stretched forward.

P2. Final Recovery. Heels are rising from the footboard and toes start pushing the stretcher, which leads to the boat deceleration and legs/seat velocity decreasing. Then, the blade is squared; and the handle is thrown away towards the stern and upwards. At the last moment (0.02-0.04s), legs are "catching" through the stretcher to create counter-movement of the blade into the water.



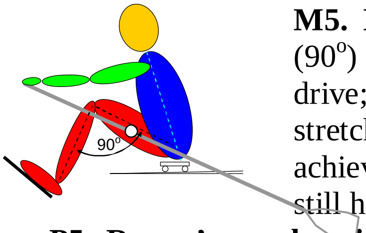
M3. Catch. The furthest position of the handle to the stern. Arms and wrists are straight; shoulders are low and extended. Low back is in straight and braced position; the chest is compressed to thighs. Shins are vertical, heels are risen from the stretcher.

P3. Blade entry. The blade sharply enters into the water with a small splash towards the stern, which is achieved by "kicking" the stretcher through the toes and knees are extended by means of fast, but "light" work of quads muscles.



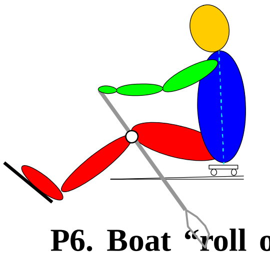
M4. Full blade immersion. The seat and handle has passed 6-10cm from the catch. The trunk keeps the catch position. The rower is "hanging" on the handle through the stretched arms and shoulders.

P4 Initial boat acceleration. The direction of blade movement becomes horizontal. The handle force quickly increases and the boat acceleration becomes positive. The rower's weight is lifting from the seat and suspending between handle and stretcher.



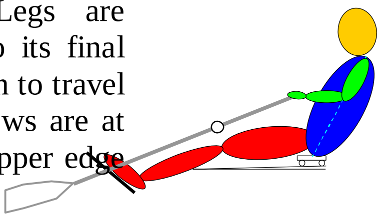
M5. Drive Transition. Square (90°) knee angle during the drive; handle on top of the stretcher. Legs/seat velocity achieves its maximum; trunk still holds the catch position.

P5. Rower's acceleration. Heels are placed onto the footboard and pushing it. The muscle activation is sharply switched from quads to gluts and hamstrings, from knee to hips extension, which "opens" the trunk, pushes the knee down and "automatically" extends it. The force and power achieve their maximums by means of usage of the biggest muscles of the body. Acceleration of rower's CM increases, but the boat acceleration decreases.



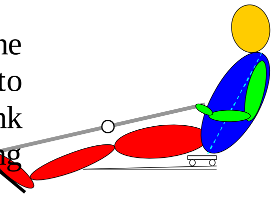
M6. Middle of the drive. The oar is close to the perpendicular to the boat and handle on top of knees. Legs are nearly straight; trunk is vertical, shoulders and arms are beginning to pull.

P6. Boat "roll out". The handle continues acceleration by means of a fast extension of the trunk as well as pulling with the shoulders and arms. Forces are decreasing, and the stretcher force decreases faster than the handle force, which causes significant boat acceleration.



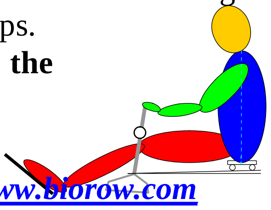
M7. Late drive. Legs are straight, trunk is close to its final position, handle has 5-7cm to travel (the less the better). Elbows are at the level of the handle. Upper edge of the blade surfaces

P7. Blade extraction. The stretcher force is sharply cut, but the arms continue fast drive of the handle forward-down. This causes the trunk to begin return movement to the stern. The rower's weight is fully transferred onto the seat. The blades are quickly and cleanly extracted from the water.



M8. Finish of the drive. The handle is in the furthest position to the bow. Legs are straight, the trunk angle is 20-25°. In sweep rowing the outer hand "brushes" the trunk.

P8. Early recovery. The handle starts moving towards the stern and the blade is feathered. The hands, arms and shoulders are smoothly extending and "follow" the handle. Then, the pelvis and trunk together are "pivoting" around flexing hips.



M1 Cycle End / Start of the next one.

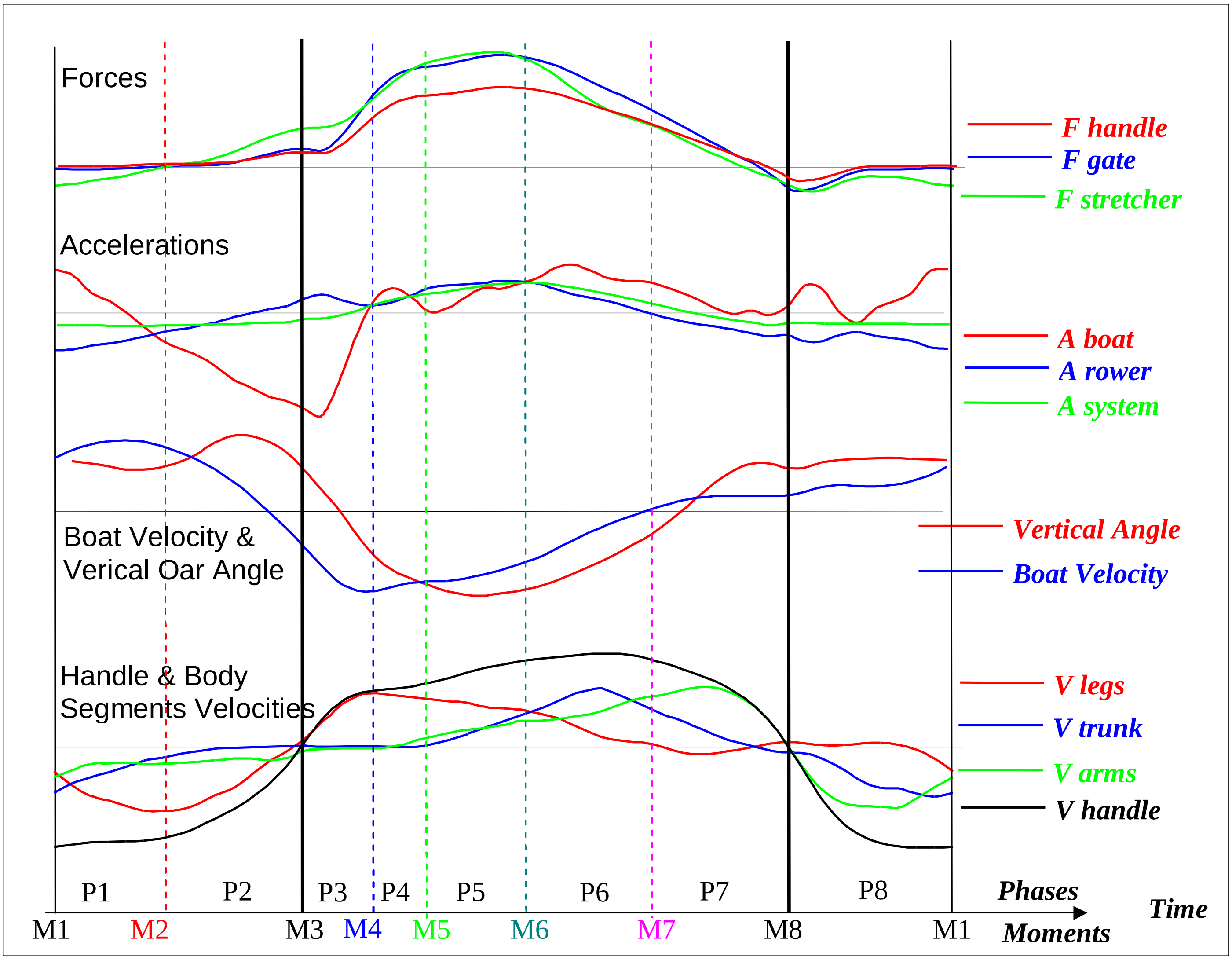


Fig.1. The main biomechanical variables during the stroke cycle

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1. 2011 Kleshnev V. Biomechanics of Rowing. In: Nolte V. (ed.) Rowing Faster. Second edition. Serious training for serious rowers. Human Kinetics. 105-121
2. 2010. Kleshnev V. Boat acceleration, temporal structure of the stroke cycle, and effectiveness in rowing. Journal of Sports Engineering and Technology, 233, 63-73.
3. 2002-2006 Kleshnev V. Rowing Biomechanics Newsletter 2002/11, 2002/12, 2004/01, 2004/10, 2006/02. www.biorow.com , www.biorow.org

BIOROW BIOMECHANICS OF ROWING
Rowing Biomechanics Newsletter No 149 2013 August

News

The World Rowing Championship 2013 has just finished in Chungju, South Korea. 10 medals were won by the teams, which BioRow had been working with during this season: 6 gold (LM2- SUI, LM1x DEN, LM2x NOR, M4- NED, M2x NOR, LM4- DEN) and 4 silver (LM1x FRA, M2- FRA, LM2x SUI, ASW1x NOR). Congratulations to the rowers and coaches! Well done!

Rower's mass suspension

Recently, we have conducted another experiment on vertical forces. In addition to the seat force (RBN 2013/04), vertical and horizontal forces at the stretcher were measured at three points, where the stretcher is mounted to the boat (Fig.1) and summed up.

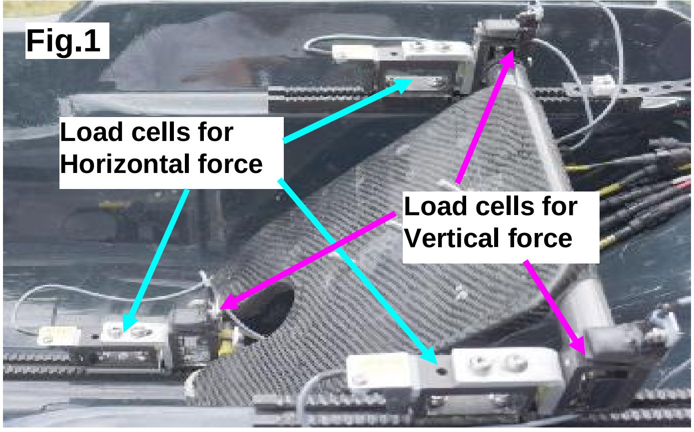


Fig.1

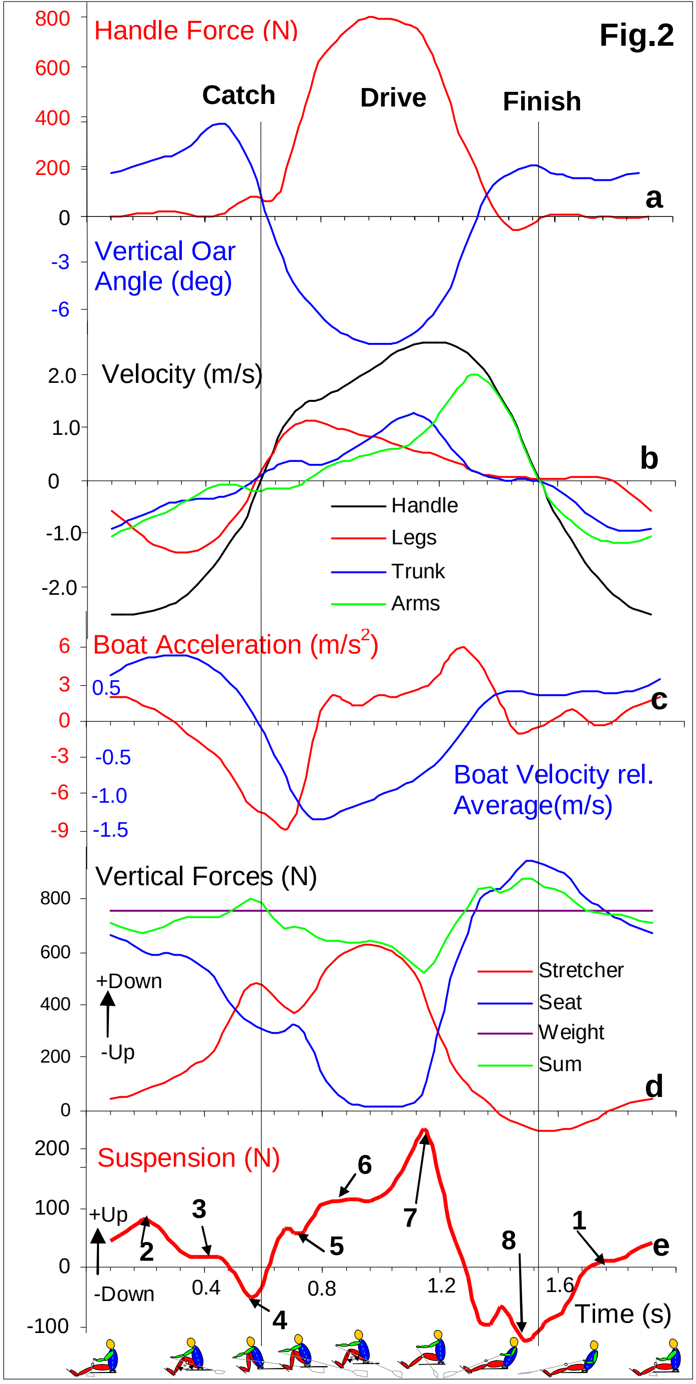
Fig.2 shows the data of a single sculler (1.87m, 77kg) at a stroke rate 32 min^{-1}. The vertical forces at the seat ***Fseat*** and stretcher ***Fstr*** were summed up and the sum was compared with the rower's weight ***Fw*** (Fig.2, d). Then the sum of the forces was subtracted from the weight, so the suspension ***Fsus*** of the rower from the boat was found (Fig.2, e):

$$Fsus = Fw - (Fseat + Fstr) \qquad (1)$$

The suspension is close to zero at the beginning of the recovery (1), when the rower's weight is placed on the seat and the vertical stretcher force is zero. Mid-recovery (2), the weight is transferring onto the stretcher and the suspension has a short peak up to 90N, which could be explained by negative vertical acceleration of the rower's CM descending on the slides. Before catch (3), the suspension is close to zero again, but this balance of forces is very dynamic: vertical stretcher force quickly increases, because the weight is being transferring from the seat.

At the catch (4), 63% of the rower's weight is located on the stretcher and only 39% left on the seat, so the suspension is negative -50N, which could be explained by upward acceleration of the arms and handles. Just after the catch (5), the suspension became positive, but the weight at this phase is transferring back onto the seat and the suspension has a little hump, which could be related to a rower's acceleration upwards on the slides and increase of the vertical handle force, which pushes him down.

During the "initial boat acceleration" phase (P4, RBN 2013/07), the weight is nearly completely lifted from the seat (only 20N left ~2%), but ~83% of it is transferred onto the stretcher (6), so only 15% of the rower's weight is suspended and makes the system rower-boat lighter. Another 50N ~4% of the vertical component of the handle force could be added (calculated at 4° pitch, RBN 2013/02), which pulls the rower down, so the real value of the suspension could be ~19-20% of the rower's weight.



At the middle of the drive (7), almost the whole weight is still lifted from the seat, the stretcher force quickly decreases, so the suspension has a sharp peak up to 230N ~30% of the rower's weight or 25% of the system weight (+18kg boat). At the finish (8), the ***Fstr*** is slightly negative, but ***Fseat*** is high (125% of ***Fw***), so the ***Fsus*** is negative -100N, which is related to vertical trunk acceleration.

<u>The suspension could make the system rower-boat 20-25% lighter, which decreases water displacement and drag resistance.</u> This research was done for the first time in the history (to our knowledge) and further experiments and analysis required

Acknowledgments. Thanks to Oarsport Ltd. and Miles Forbes-Thomas of BetterRowing for support of the study.

BIOROW BIOMECHANICS OF ROWING **Rowing Biomechanics Newsletter** No 150 2013 September

What causes rower's mass suspension?

We have received interesting feedback on our findings about rower's suspension published in the previous Newsletter. Dr. Volker Nolte, a professor of Western Ontario university, Canada, noted that the only reason of suspension is the inertial force created by vertical acceleration a_{CM} of rower's CM (centre of mass) m_{CM}. His version of the equation 1 from RBN 2013/08 is the following:

$$\Sigma_F = F_{FootV} + F_{seat} + F_{HandleV} - W = m_{CM}\, a_{CM} \qquad (1)$$

In this case, the average suspension force Σ_F over the stroke cycle must be zero, because the average vertical acceleration of rower's CM must be zero. However, in our measurement the average suspension force was 43N in that data sample. If it explained only by acceleration of the rower's CM, then its position would be about 1m lower after each stroke cycle, i.e. 100m below water level after 100 strokes, which is not possible. Another obvious evidence of existence of the suspension can be seen with naked eye: the boat if lifted up by 3-4 cm during the drive (Fig.1, 1), which corresponds to 15-20kg lighter rower's weight and close to the measured suspension force.

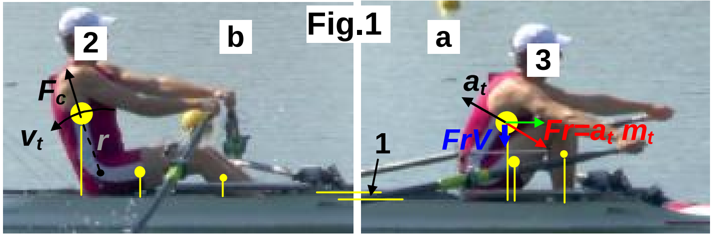


Fig.1

Volker's counter-arguments were the following: 1. The offset of the average suspension force could be explained by error in the measurements. 2. The visible vertical movements of the hull could be explained by water-forces: it sinks into the water since the water has a velocity relative to the hull and the pressure lowers, more during recovery, when the velocity is higher.

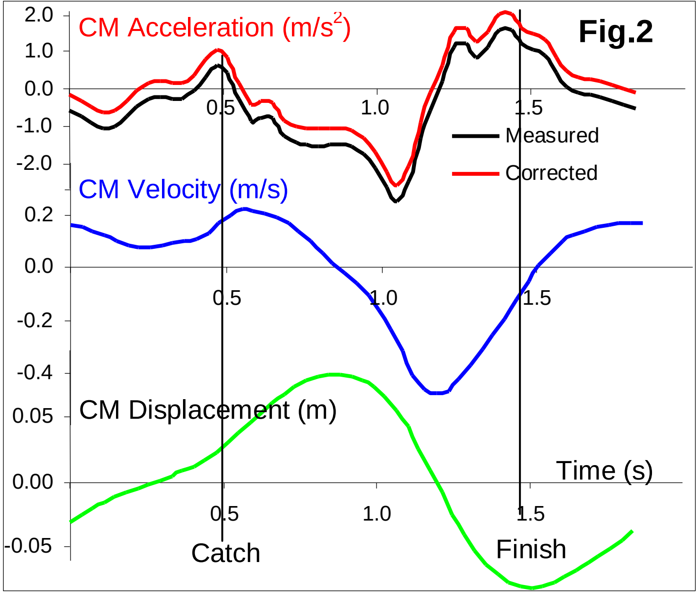


Fig.2

To check Volker's hypothesis, we have added an offset to the measured suspension force to make average acceleration of rower's CM over the stroke cycle equal to zero (Fig.2). However, the derived displacement of the rower's CM looks very strange: its position at the middle of the drive ~12cm higher than at the middle of recovery, which makes this hypothesis quite unlikely.

Another interesting hypothesis came from a master's rower and an engineer Tor Anderson of Los Gatos Rowing Club, CA, US: "It looks like peaks in suspension force occur when the body swings, both on the drive (7, Fig.2, RBN 2013/08) as well as the recovery (2). It seems one of the contributions to these peaks is centripetal force F_c of the body swing, acting in the vertical direction:"

$$F_c = m_t\, v_t^2 / r \qquad (2)$$

where m_t – mass-moment of the trunk with head, v_t – its instantaneous linear velocity, r - radius of inertia from the centre at hips joint (Fig.1, 2). Plugging the data m_t = 25kg, v_t = 1.25 m/s, and r = 0.4 m (roughly 50% of the height of the torso with head), we got a force of ~100N in the vertical direction, which is close to the magnitude of the bump 7 during the drive.

However, it was decided that the centripetal force can not be the reason for the fact that the average suspension force over the stroke cycle is higher than zero. Upwards centripetal force should be balanced by downwards the reaction force ***FrV*** (Fig.1, 3) caused by the trunk acceleration at the catch and finish.

So, **the mechanics of the suspension force is still not completely clear** to us. More experiments and analysis needed.

Normative data in rowers' groups

Statistical analysis was conducted on the data obtained in various levels of rowers in our standard test (RBN 2013/03). Five rower's groups were defined:

1. **Beginners** – rowers with little experience of qualified coaching;
2. **Students** of universities and colleges aged 17-21;
3. **National** level rowers of various ages – not members of national teams;
4. **International** level rowers
5. **Champions** – medallists of Olympics and Worlds.

The deviations from the target values for each rowers' category (male/female, sweep/sculling, LW/HW, RBN 2009/05) were obtained and averaged in the rower's levels. Table 1 shows how much the main mechanical variables (stroke length and average force) LOWER than targets:

Table 1	n	Length	Force
Beginners	53	>8%	>30%
Students	245	5-8%	20-30%
National	222	3-5%	12-20%
International	162	1-3%	5-12%
Champions	15	<1%	<5%

The table could be used for evaluation of results of biomechanical testing.

The reasons of lift force in rowing

Two further experiments were done to investigate the reasons of the lift force. A Concept2 erg was mounted on slides through three sensors measuring the whole weight force of the erg with a rower (Fig.1). The lift force was derived as the difference between static weigh and measured vertical force during rowing. The erg was instrumented to measure handle force and positions of the handle, seat and trunk.

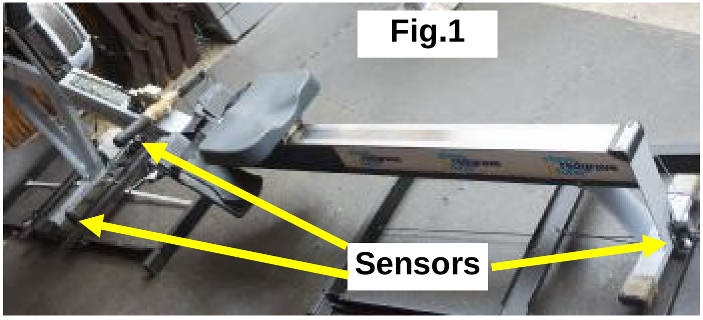


Fig.1

Three samples were taken 10 strokes each with various techniques: a) legs only (stroke rate 44 str/min), b) trunk only (41 str/min) and c) full length (36 str/min). As it was expected, the average lift force over stroke cycle was zero in all samples.

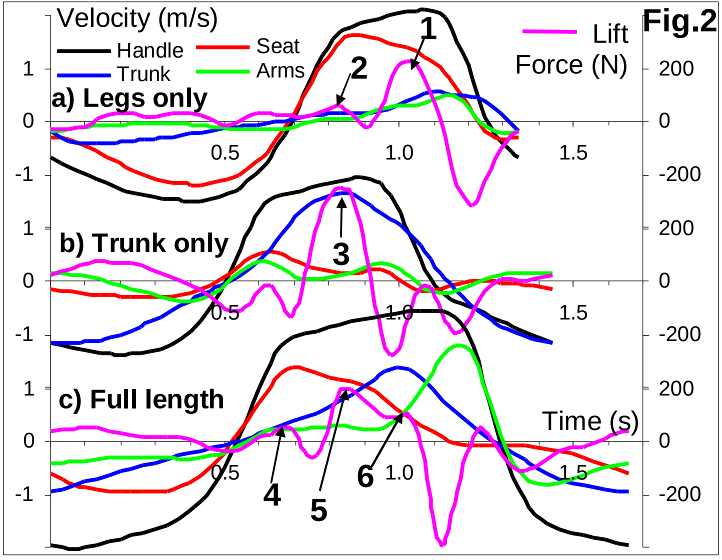


Fig.2

Maximal lift force at "legs only" rowing was 220N (Fig.2) and it appeared at the second half of the drive (1), when seat velocity is getting slower and thighs and shins are going down. Much smaller lift force 55N was measured at maximal seat velocity (2). Lift force at "trunk only" rowing was the most significant with a peak 350N, which happened at the maximal trunk velocity (3). The lift force at "Full length" rowing had even three peaks: at max. seat velocity (4), at max. trunk velocity (6) and the biggest one 190N in between them (5).

The second experiment was done in a mobile rowing tank "BRIS" (Fig.3), where two sensors of vertical force were mounted between a trolley and a frame with rower's workplace ("boat"), so they measured the whole weight of the rower with the "boat", minus buoyancy force. Also, oar angles, handle force and positions of seat and trunk were measured. Similar three samples were taken 10 strokes each at 40, 37 and 33 str/min correspondingly. The average lift force over the stroke cycle was more than zero: 33, 39 and 30N, which was 9-13% of the average handle force. This could be explained by vertical force at the blades at 6° pitch (sin(6°) = 10.5%). Though this average value of lift force is similar to what we've measured on-water (RBN 2013/08-9), its nature is different: on water, the forces were measured between the rower and boat frame, but here the forces were measured between the "boat" with rower and external support. Therefore, external vertical blade force was measured as the lift force in this case, but on water the vertical handle force pushed the rower downwards and decreased the lift force between rower and boat. Positive offset of the average lift force on water, could, probably, be explained by transfer of a part of vertical force through calves when they touch the boat at the end of the drive.

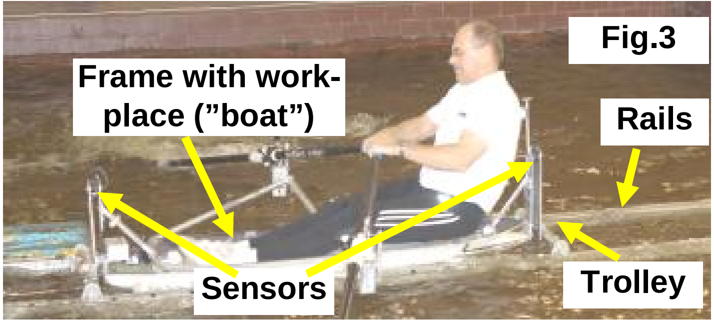


Fig.3

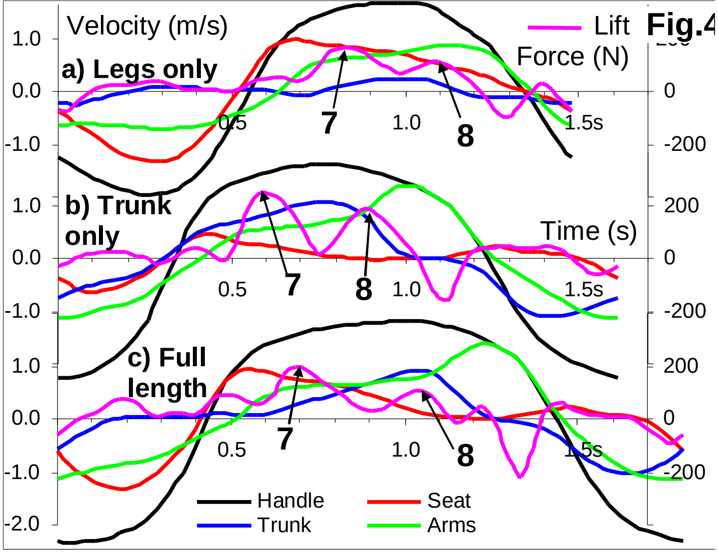


Fig.4

Dynamics of the lift force was quite similar to the erg (Fig.4): it had the highest magnitude 250N at "trunk only" and 170-200N at "legs only" and "full length" rowing. Peaks occurred after max. seat velocity (7), and coincides with the peak trunk velocity (8).

Conclusions: 1. Centripetal force of the trunk rotation appeared to be the main factor of the lift force during rowing.

2. Smaller lift caused by vertical acceleration of legs at the second half of their drive.

3. Vertical blade force is the only external factor lifting the whole system boat-rower, but it is relatively small.

Acknowledgements. Thanks to Sergey Belousov of Saint-Petersburg Sport Institute, Russia for his kind offer to use his "BRIS" rowing tank in the experiment.

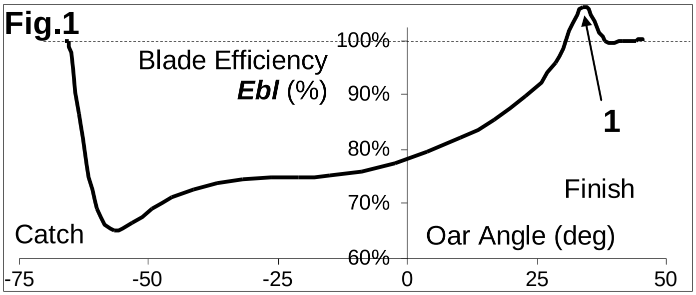
Oar blade as a jet engine

We already discussed the blade propulsive efficiency E_{bl} a number of times (RBN 2006/06, 2007/12, 2012/06), but still not completely satisfied with understanding of this important variable. Previously, E_{bl} was defined as a ratio of the propulsive power ***Pprop*** to the total power produced by a rower ***Prow***:

$$Ebl = Pprop / Prow = (Prow - Pw) / Prow \qquad (1)$$

where ***Pw*** is the waste power, which is lost on moving the water, when the blade "slips" through it. Fig.1 shows typical curve of ***Ebl*** in a single at 32 str/min. It looks like the blade efficiency increases towards the finish of the drive and becomes even higher than 100% (1), which confuses rowers and coaches.

Fig.1



A new idea came after a brief talk to aviation engineer during Ukrainian rowing seminar in Kiev, who asked: "Does the blade work as a jet engine or as a car wheel?" It looks like the first case is the right answer, because it is not possible to move on the water without moving it backwards.

In aviation and rocketry, a **specific impulse *Isp*** is the main way to describe the efficiency of jet engines. It represents the thrust force ***Ftrust*** with respect to the mass of propellant ***m*** used per time unit ***t***:

$$Isp = Ftrust / (g\ m / t) \qquad (1)$$

where ***g*** is gravity acceleration. ***Isp*** depends on velocities of exhaust gases ***Vg*** and the jet vehicle ***V***:

$$Isp = (Vg - V)\ m / t \qquad (2)$$

Efficiency of jet vehicle ***E*** is also related to ***Vg*** :

$$E = 2 / (1 + Vg / V) \qquad (3)$$

Efficiency and specific impulse are reversely related. At the start of runway, the efficiency of a jet plane is zero, because its velocity is zero, but the thrust and specific impulse are maximal. As the plane accelerates, its efficiency increases, and became 100%, if the plane speed is equal to the speed of exhaust gases, but the thrust and specific impulse became zero then. Therefore, design of a jet engine is a balance between its efficiency and thrust.

Similar things happen in rowing: at catch, the velocity of the rower-boat system is the lowest; then, it increases during the drive till the finish. Therefore, the propulsive power increases during the drive, as it is a product of propulsive force and velocity of system CM. Hence, the blade propulsive efficiency increases and became higher 100%, when the system velocity became higher than blade velocity. However, it doesn't mean the blade works better.

Of course, rowing is not exact jet propulsion and rower's energy substrates are not thrown directly backwards to create the thrust. However, jet fuel means energy, the energy per time is power, so, we decided to substitute the fuel flow used in jet engines with mechanical power produced by a rower ***Prow*** and define the specific impulse ***Isp*** of the blade as following:

$$Isp = Ftrust / Prow \qquad (4)$$

The previous definition of blade efficiency ***Ebl*** was dimensionless, but ***Isp*** has a dimension in ***s/m***, i.e reversed velocity, while dimension of ***Isp*** in jet engines is ***s***. To calculate ***Isp***, rowing power ***Prow*** was derived using traditional method (see RBN 2004/06):

$$Prow = Fh\ Vh \qquad (5)$$

where ***Fh*** and ***Vh*** – handle force and velocity. The blade thrust ***Ftrust*** was derived as:

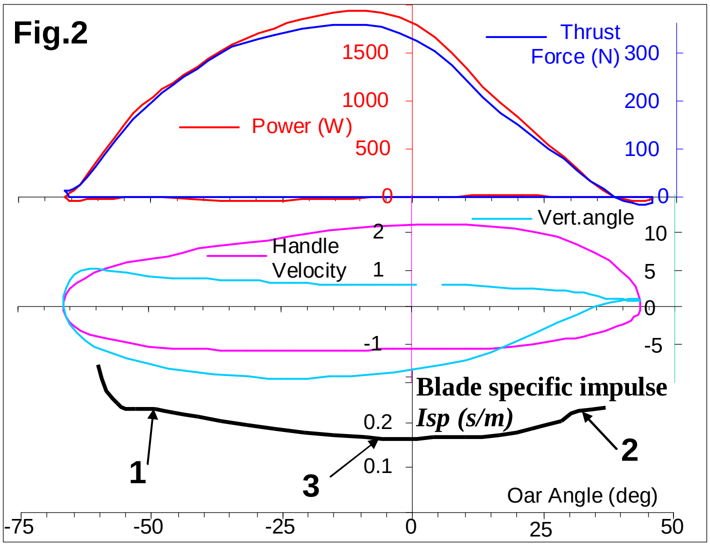
$$Ftrust = Fh\ (Lin / Lout) \cos(\alpha) \qquad (6)$$

where ***Lin*** and ***Lout*** - actual inboard and outboard (from pin to centre of the blade) and ***α*** - oar angle. Combining equations 2, 3 and 4 we can get:

$$Isp = (Lin / Lout) \cos(\alpha) / Vh \qquad (7)$$

Fig.2 shows power, thrust, handle velocity, vertical oar angle and ***Isp*** for the same data as on Fig.1:

Fig.2



The blade specific impulse ***Isp*** looks quite even during the drive. Its higher value ~0.23 s/m was found at the beginning and the end of the drive (1, 2); the lowest 0.16 s/m - at the perpendicular position of the oar (3). The average ***Isp*** of underwater blade work was 0.19 s/m at this sample. It decreases at higher stroke rates and boat speeds from 0.27 at rate 20 down to 0.17 s/m at 41 str/min.

Conclusions: **The specific impulse can be used together with blade efficiency for evaluation of the blade work. A higher specific impulse is generated at a lighter gearing ratio, but at a lower handle velocity at the same time.** Obviously, this is possible only when the blade has significant resistance in the water, which could be achieved either by **using bigger blade area, or by more effective thrust production using a better shape and/or utilisation of hydro lift effect**, which happens at the beginning and the end of the drive.

Blade efficiency and effectiveness

The blade specific impulse introduced in the previous newsletter could be considered as a measure of its effectiveness (performance), which is often differently directed to efficiency (RBN 2011/10). Similar opposition can be seen in aircrafts, where efficiency increases with the speed, but performance decreases (Fig.1), so the design of the engine is defined by both cruising speed and takeoff requirements.

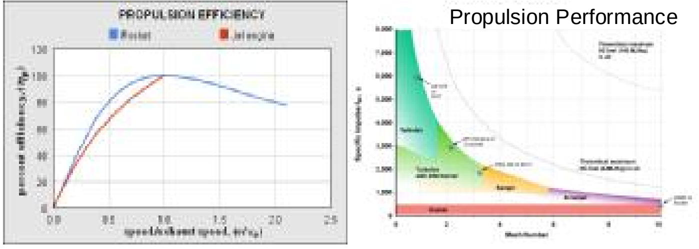


Fig.1. From http://en.wikipedia.org/wiki/Jet_engine

We have done similar analysis for the first eight strokes at the standing start in LM1x (Fig.2):

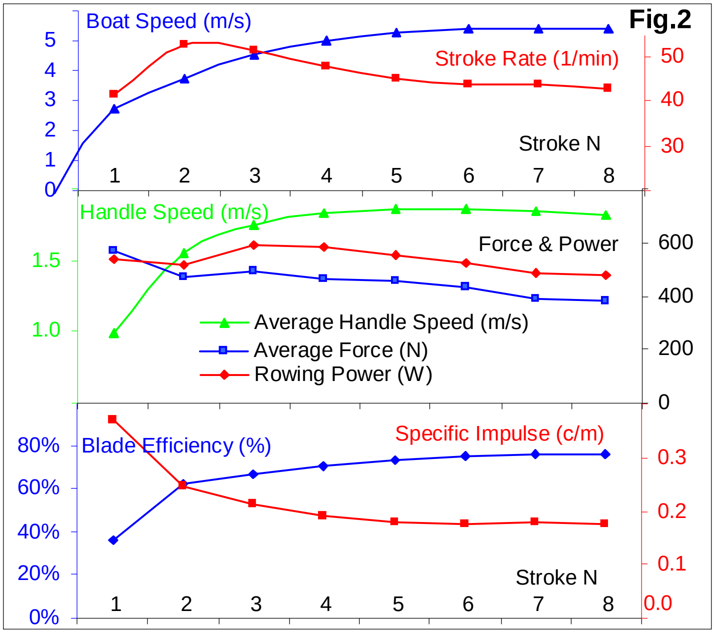


Fig.2

After the first stroke, boat speed increases up to about half of those at cruising speed; blade efficiency has the lowest value 36% only, but specific impulse has the highest value 0.37 s/m. Then, boat speed increases and achieves its constant level after the sixth stroke; but average handle force drops down by 33%, which could be explained by Hill's law of muscle contraction (RBN 2007/09). Work per stroke and rowing power ***Prow*** remains nearly constant, because lower force is compensated by longer stroke length and higher handle velocity. Blade efficiency ***Ebl*** increases more than two times up to 76%, because it depends on propulsive power ***Pprop***, which is proportional to the velocity of the system CM V_{CM}:

$$Ebl = Pprop / Prow = Fprop\ V_{CM} / Prow \qquad (1)$$

After six strokes, specific impulse ***Isp*** decreases two times down to 0.18 s/m, because propulsive force ***Fprop*** decreases and handle velocity increases (the last is reversely proportional to ***Isp***, Eq.7 in RBN 2013/11), so the rower has to spend more power to provide less thrust.

Similar things happen during the stroke cycle, when velocities of the boat and CM of the rower-boat system vary. Fig.3 shows blade efficiency and effectiveness (***Isp***) of LM1x at stroke rate 32 1/min. The bottom chart shows power ***Prow*** produced by the rower, power transferred into kinetic energy of the system ***Pkin***, power spent on drag at the hull ***Pdrag*** and waste power ***Pw*** of the blade slippage in the water.

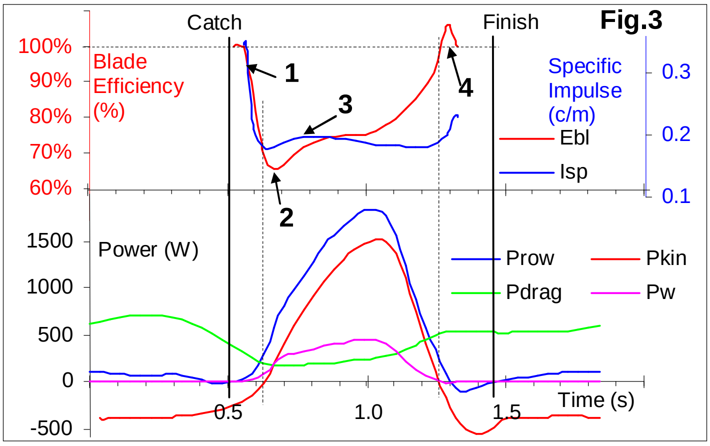


Fig.3

At the catch (1), both blade efficiency and effectiveness are high because the power production ***Prow*** is less than drag power ***Pdrag*** and ***Pkin*** is negative, so kinetic energy of the system is spent on overcoming the drag and, partly, on moving the blade forward through the water together with the boat. As power production starts increasing, but the system CM velocity is still close to its minimum, the blade efficiency has its lowest value (2). During the drive, it increases together with the system velocity and ***Pkin***. Contrarily, the specific impulse is quite constant during the drive and has only a small maximum (3) at the **oar angle -40-45° at catch**, which **could be considered as the most effective position for the force application**.

At the finish, the velocities of the boat and system CM increase together with drag power, but rower's power production decreases. At a +30-35° oar angle ***Prow*** becomes lower than drag power ***Pdrag*** (4), the system starts decelerating and ***Pkin*** becomes negative. This means kinetic energy of the system is spent on moving the boat forward together with the blade, while there is still some backwards force at it. It could probably be explained by the hydro lift effect. Product of this forward blade velocity (with the boat) and backward force creates negative "waste power" ***Pw*** and ***Ebl***>100%. **At the finish, the blade efficiency becomes higher than 100%, but this doesn't indicate effective blade work.** Similar to a jet plane, if it suddenly puts engines to low power and exhaust gases become slower than the plane speed, then the efficiency of the jet engines will be more than 100% (Eq.3 in RBN 2013/11), but the thrust became lower than drag, so the plane can't sustain flight very long.

Best wishes for the Christmas and New Year 2014!