Q&A

Q: We have received a number of positive replies to our spreadsheets on the ratio of speed to stroke rate on water and on erg (RBN 2007/10). The most common question was: "**How the speed/rate ratio depends on the duration of the exercise?**" In other words: "If we know some normative speed/rate data for one distance, how can we extrapolate for another workout?"

A: To answer this question, we need to derive an equation describing dependence of speed and power (***y***) on the distance and time of the workout (***x***). Previously, the power or logarithmic functions were used for this purpose (1). The power function $y=x^a$ was used here for simplicity. Instead of absolute values of speed ***V*** and distance/time ***D/T***, their ratios (%) to corresponding values obtained in 2k race were used:

$$rV = rD^p \quad (1) \qquad\qquad rV = rT^q \quad (2)$$

Two sources of data were used, both obtained on Concept2 ergometer: the world best times at various distances (2) and average data on a group of 20 elite rowers (unpublished data). The last sample fits very well with the power regression line (R^2=0.99), but world record data has lower determination (R^2=0.96) because of some outliers (e.g. world men's record on 500m 1:10.5 = 119.4% to 2000m record 5:36.6):

Fig.1

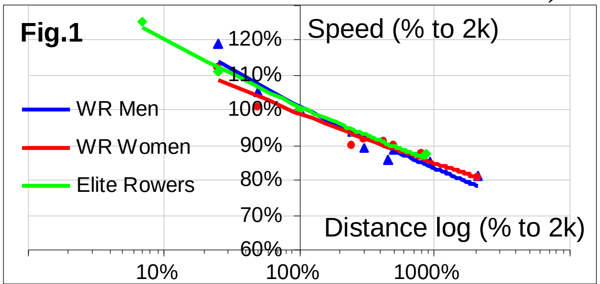


Fig.1 shows that men have higher factor in the equation 1 (p=-0.08385) than women (p=-0.07104). This means **men are better sprinters, while women are relatively better in long distances**. The general factors in all studied groups were found as p=-0.07748 and q=-0.07228.

Let's leave to physiologists the discussion of the sources of metabolic energy at various distances; here we are interested in pure mechanical aspects. The 2nd and 3rd columns of Table 1 show normative percentages of speed and power at various distances based on general trends.

To achieve the variation of power ***P*** at various distances, a rower has two options: vary stroke rate ***R*** or work per stroke ***WPS***:

$$P = WPS / T = 60\ WPS\ R \qquad (3)$$

(where ***T*** is duration of the stroke cycle)

Practically, WPS means force application, because the stroke length usually does not change much and even has an opposite trend: it is getting shorter at higher rates. Usually, both options are used together. Rowers use higher stroke rate and apply more force at shorter distances, and vice versa, so "constant WPS" method doesn't make sense here.

Various strategies can be used to vary power and speed. Some rowers and crews prefer to vary stroke rate and maintain forces more or less constant. Others vary force application quite significantly. Also, various strategies could be used at shorter and longer distances:

- At short distances a rower may not have enough capacity/skills to increase speed and stroke rate, and have to use higher force and WPS.
- At long distances, force and WPS may drop due to muscles fatigue, which must be compensated with the stroke rate.

Stroke rate and force application must be optimised individually to achieve the best performance. In the last four columns of the Table 1 we tried to give a feeling of how stroke rate and force application may vary, when using different strategies. Percentages of "Effect of the stroke rate" show its share in the variation of power/speed:

- 100% means all variation of power is achieved by the variation of stroke rate while WPS remains constant.
- 50% means variation of the power is produced by equal variations of both stroke rate and WPS, etc.

Racing stroke rate 34 str/min was used as the most common for 2k race distance.

Table 1			Effect of the stroke rate (1/min)			
Distance (m)	**Speed (%)**	Power (%)	25%	50%	75%	100%
250	**117.5%**	162.2%	39	45	50	55
500	**111.3%**	138.0%	37	40	44	47
1000	**105.5%**	117.5%	35	37	38	40
2000	**100.0%**	100.0%	34	34	34	34
5000	**93.1%**	80.8%	32	31	29	27
6000	**91.8%**	77.5%	32	30	28	26
20000	**83.7%**	58.6%	30	27	23	20

Tables in the attached spreadsheet (3) give more detailed information on these variables with one additional dimension - relative intensity. In training athletes usually perform exercise with efforts lower than in racing (100% of their speed/power at the given distance), so percentage of intensity shows speeds at corresponding relative efforts. These tables would work perfectly on an erg, because the indicated speed is impacted by power only. In a boat speed is affected by weather conditions. In the spreadsheets users can input their own data, calculate individual factors in power equations 1, 2 and compare them with the general trends. This exercise will indicate if the rower/crew is better in sprinting or in long distances.

References

1. Gordon S.M. 2008. Sport training. Moscow, FK, 256
2. World best times on Concept2 ergometer. www.concept2.com
3. Rowing Distance-Speed-Rate Calculator. http://www.biorow.com/RBN_en_2012_files/Distance-Speed-Rate%202012%2001.xls

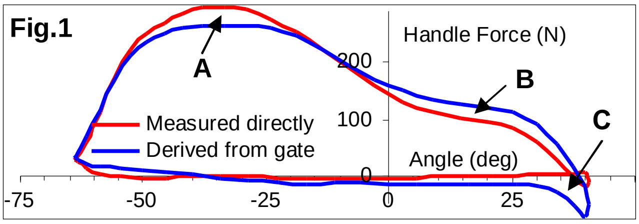
In the front line of research

Recently, we have tested a newly developed instrumented gate (1) with six single scullers of different level and sex. The main purpose was to compare and verify force measurements and power calculation with our standard method: measuring handle force using detection of the oar bend. We already discussed various methods of the force measurements in RBN 2010/03. As the new sensor measured gate force $\mathbf{F_{gate}}$ in a perpendicular direction to the oar, the handle force $\mathbf{F_{hnd}}$ was derived as:

$$\mathbf{F_{hnd} = F_{gate}*(L_{out}/(L_{in} + L_{out})) = F_{gate}* (L_{out}/L_{oar})} \qquad \mathbf{(1)}$$

, where $\mathbf{L_{in}}$ is actual inboard (from the pin to the centre of the handle), $\mathbf{L_{out}}$ is actual outboard (from the pin to the centre of the blade) and $\mathbf{L_{oar}}$ – actual oar length equal to the sum of the first two values. Fig.1 shows force curves obtained using the above two methods in W1x at stroke rate 30 str/min:

Fig.1



It was found that force curves were slightly different:

- Directly measured handle force was higher during the first half of the drive (**A**);
- Derived handle force was higher at the second half of the drive (**B**);
- Gate sensor measured some negative force at the beginning of recovery (**C**), which can be explained by inertial force of fast accelerating oar. Oar sensor is not detecting this force because the oar is already feathered.

The power **P** was derived as:

$$\mathbf{P = F_{hnd} * L_{in} * \omega} \qquad \mathbf{(2)}$$

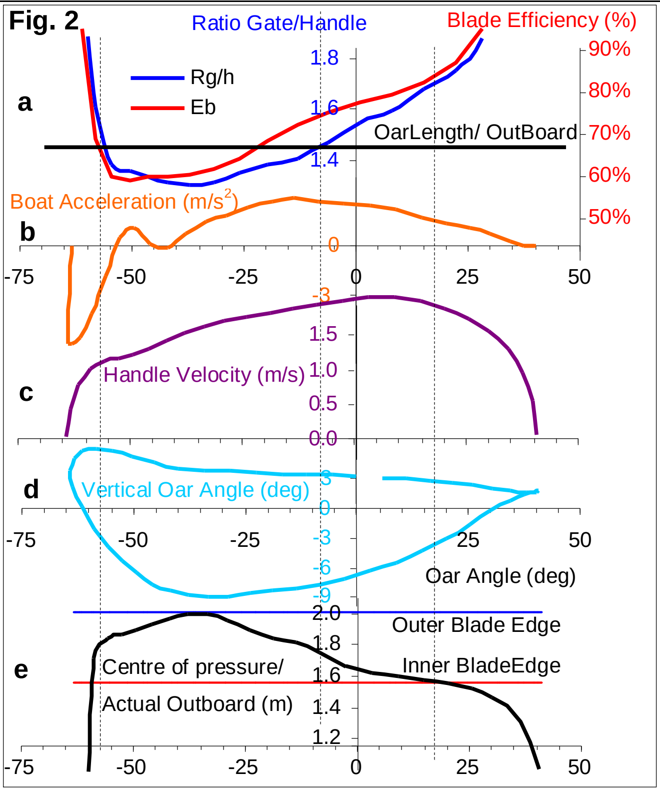
where $\boldsymbol{\omega}$ is angular velocity of the oar. It was found that values of power calculated using these two methods corresponded quite well: the average difference was 0.45%±0.17% (min. 0.11%, max. 1.07%). This allows us to conclude that the **new gate sensor can be reliably used for measurements of rowing power**.

Then, we tried to analyse the reasons for the differences in the force curves measured at the gate and at the oar handle. The ratio of these two forces ***Rg/h*** was derived, which from the equation (1) should be equal to the ratio of the actual oar length to outboard:

$$\mathbf{Rg/h = F_{gate}/ F_{hnd} = L_{oar} / L_{out}} \qquad \mathbf{(3)}$$

When this ratio was plotted against oar angle (Fig.2a), it was amazing that the curve resembles the blade efficiency curve (***Eb***, RBN 2007/12). It is very unlikely that this resemblance could be explained by some systematic error of sensors because these two variables were derived completely independently: ***Rg/h*** from two force sensors, ***Eb*** – from the boat velocity, angular velocity of the oar and outboard.

Fig. 2



The black horizontal line on the Fig.2a represents ratio of the actual levers $\mathbf{L_{oar}/L_{out}}$ derived geometrically, i.e. assuming that the resultant forces applied at the centres of the handle and blade. The ratio of forces ***Rg/h*** was equal to the ratio of levers $\mathbf{L_{oar}/L_{out}}$ at the middle of the drive, close to the perpendicular position of the blade. During the first half of the drive the ratio of forces was lower than ratio of levers, which could happen due to one of three reasons or a combination of them:

- If the actual outboard is longer, i.e. the resultant blade force is applied closer to the outer edge;
- If the actual inboard is shorter, i.e. the resultant handle force is applied closer to the inner edge;
- Inertia force caused by angular acceleration of the oar.

During the second half of the drive the ratio of forces ***Rg/h*** was higher than ratio of levers $\mathbf{L_{oar}/L_{out}}$, which could be explained by reversed reasons mentioned above.

It is unlikely that the actual inboard could be changed significantly in sculling, because in this case the resultant force should be applied far outside the handle. Also, small inertia force should not be a reason, because angular acceleration of the oar is very small during the drive.

Therefore, we have only one trustworthy reason left: variation of the actual outboard, which was already mentioned before (RBN 2003/08). It could be related to specifics of the blade hydrodynamics at various oar angles, depth (Fig.2d) and applied forces, which also affects blade efficiency, so the curves are similar. Fig.2e shows that **the derived centre of pressure moves outside of the blade at the end of the drive**. The reasons of these phenomena are not clear to us. All hypotheses are welcome.

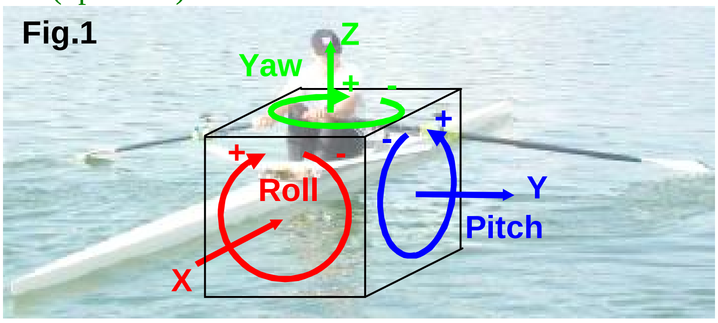
References

1. BioRowTel Rowing telemetry system, http://www.biorow.com/PS_tel.htm

Rotational motions of the boat

There are three main axes in any vessel, called longitudinal X, lateral or transverse Y and vertical Z axes (Fig.1). The rotational movements around them are known as roll, pitch and yaw:

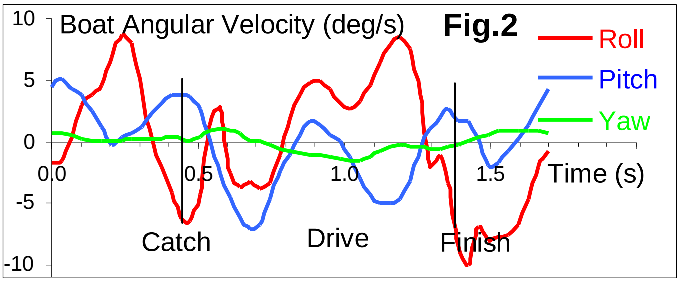
- Roll is when the boat rotates about the longitudinal X (front/back) axis.
- Pitch is when the boat rotates about the lateral or transverse Y (side-to-side) axis.
- Yaw is when the boat rotates about the vertical Z (up-down) axis.



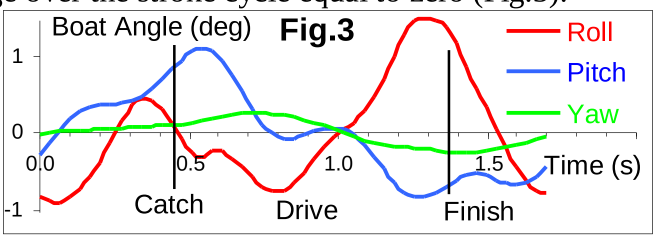
BioRowTel measurement system (1) is equipped with 3D gyroscope, which allows measurement of angular velocities of the boat rotation around all three axes. The agreement on the directions was made:

- Positive Roll is the port board up.
- Positive Pitch is the bow up, stern down.
- Positive yaw is the bow turning to starboard.

Fig. 2 shows angular velocities of the hull in a single sculler at a stroke rate of 35 str/min:



Angular velocities are difficult to interpret and make meaningful for a coach and rower. They were integrated into angles of roll, pitch and yaw, and then offsets were added to each of them to make the average over the stroke cycle equal to zero (Fig.3).



Though these angles are not strictly connected to the reference frame of the Earth/water, they are useful for evaluation of relative rotational motions of the boat and could be interpreted in the following way:

Roll is quite close to zero at the catch, when the boat is balanced. Then it became negative near to -1^{o} (the right gate - port side goes down), which is the consequence of separation of the oar handles during the drive (RBN 2011/07). At the finish, the boat rolls on other side by more than $+1^{o}$ (left gate down), because the sculler pulls the handles at even height, but the gates height is different. During the recovery the boat roll repeats this cycle.

The boat pitch has its highest positive value $+1^{o}$ (stern goes down) soon after the catch, which is related to transfer of the rower's weight from seat to the stretcher (RBN 2011/03). At the middle of the drive the pitch remains close to zero (the boat is balanced). At the finish the pitch became negative close to -1^{o} (bow goes down), which is explained by increased seat force and upwards force at the stretcher due to return of the trunk (RBN 2006/10).

The boat yaw is close to zero at the end of recovery and became positive at about $+0.3^{o}$ after catch, which is explained by asymmetry of the force application in this sculler: his right arm is pulling stronger to separate handles at the middle of the drive (RBN 2011/07). Then, the boat yaws on other side because left arm is catching up, and the minimal yaw value about -0.3^{o} was achieved at the finish. During recovery, the yaw decreases to zero, which could be explained by the stabilising action of the fin.

The following table shows statistics of our measurements of amplitude (differences between maximal and minimal angles) of the roll, pitch and yaw:

Boat Type	n	Roll (deg)	±SD	Pitch (deg)	±SD	Yaw (deg)	±SD
1x	492	2.70	1.45	1.39	0.27	0.65	0.26
2-	185	1.42	0.81	1.29	0.16	0.58	0.16
2x	317	1.42	1.03	1.24	0.16	0.42	0.21
4-	137	0.53	0.64	1.01	0.15	0.45	0.15
4x	60	0.54	0.60	0.88	0.08	0.11	0.03
8+	35	0.14	0.08	0.81	0.43	0.05	0.01

The roll amplitude is the highest in singles and significantly decreases in bigger boats, nearly down to zero in eights, which is the most stable boat. Interestingly, there is no significant difference in roll between sweep and sculling boats.

Surprisingly, the difference in the pitch amplitude in various boats was relatively small: in the eights the pitch is only 40% less than in singles. The pitch amplitude significantly increases with the stroke rate (r = 0.86), which is explained by higher inertia forces.

The yaw amplitude is also reversely proportional to the boat size, decreasing nearly down to zero in eights. It pairs it slightly higher than in doubles and in fours - significantly higher that in quads, which is explained by the rigging asymmetry (RBN 2008/01, 2009/11).

All rotational motions of the boat should be minimised: pitch and yaw could increase drag resistance; roll may decrease power production and lead to injuries.

References

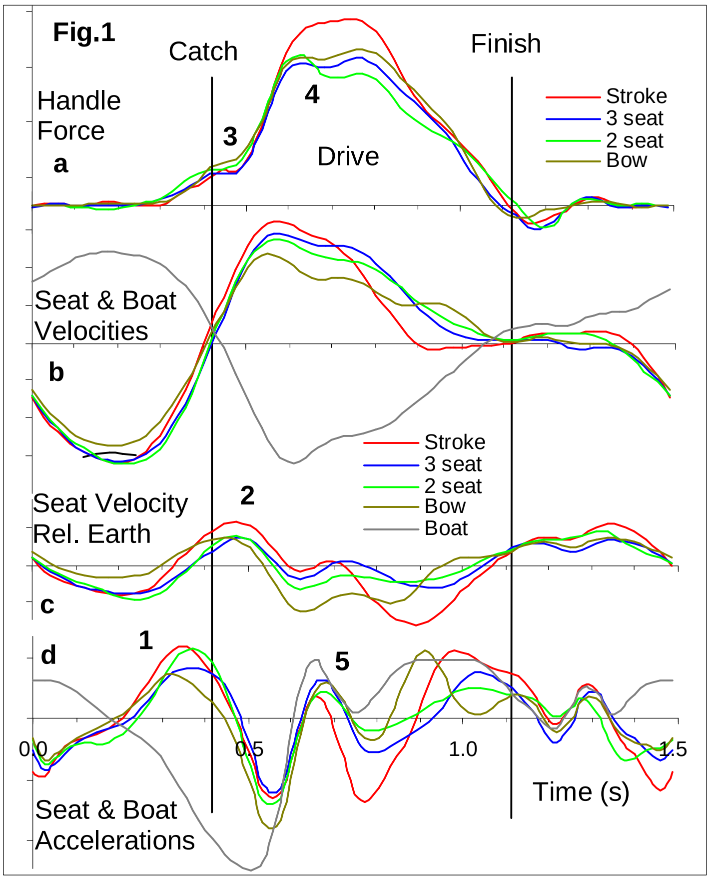
1. BioRowTel Rowing telemetry system, http://www.biorow.com/PS_tel.htm

Power transfer between rowers through the boat

During many years of testing, we noticed that rowers on stern seats usually produce more force/power than rowers in bow seats, especially in pairs, fours and eights. Coaches usually put the strongest rowers at stroke, but this doesn't explain all of observed differences in power of up to 30%. Recently, we obtained data, which allows enlightening this phenomenon. A top international level four conducted the same 6x5min step-test both on Concept2 stationary erg and on-water with power (***P***) and heart rate (***HR***) measurements. Because HR was slightly different during these two tests, second-order polynomial trends (R^2>0.99) were derived using ***P*** and ***HR*** data on erg for each rower:

$$P = a\,HR^2 + b\,HR + c \qquad (1)$$

Values of power were calculated for each rower using individual coefficients of above function, where the argument was HR on-water in each sample. These values were compared with on-water power and ratios were derived. Simply speaking, ratios of power on-erg/on-water at the same heart rate were derived for each rower. This ratio was 85.8% for the stroke, 79.3% for 3 seat, 82.2% for 2 seat and 77.7% for bow, so the rowers in the middle of the boat apply 3-6% less power than on erg compared to stroke rower, and for the bow this difference was 8%.

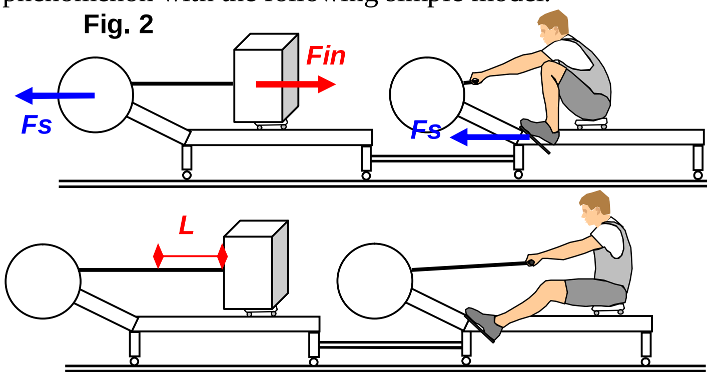


To find reasons of this phenomenon, measured patterns of handle force (Fig.1, a), seat and boat velocities (b) were analysed. Seat velocities for each rower (measured relative to the boat) were summed up with the boat velocity, so seat velocities relative Earth coordinate system were derived (c) and differentiated into accelerations (d). We assume that these seat variables were quite close to velocities and accelerations of centre of mass (CM) of each rower.

At the catch, stroke rower accelerates his seat/CM earlier (1) and achieves faster velocity (2) than teammates. As the blades are at the entry stage and forces are low (3), it is quite easy for the stroke to do. When blades go deeper into the water and forces increase to their maxima (4), it is a turn for other rowers to accelerate their masses (5). Therefore, they have to push the stretcher harder than the stroke, who already moves fast. This extra force is transferred through the stretcher-hull-rigger-pin and applied to the gate of the stroke rower, so his measured handle/blade force became higher. In other words, **one rower can transfer power through the stretcher, boat and rigger to the gate and oar of other rower**.

Notice, that acceleration of CM plays the only role in this effect, not position of the rower in the boat. Bow rowers usually accelerate their CM later, probably, because they focus on synchronisation of handle movement and pay less attention to work through the stretcher. Also, higher efficiency of the stroke rower could be explained by better utilisation of large legs muscles and faster single-motion movement, which is called "rowing using the mass".

We received anecdotal evidence that similar phenomenon also occurs on ergs: when a number of them are connected on slides, the "stern" rower usually shows higher score than normal. This gives us an idea to illustrate the phenomenon with the following simple model.



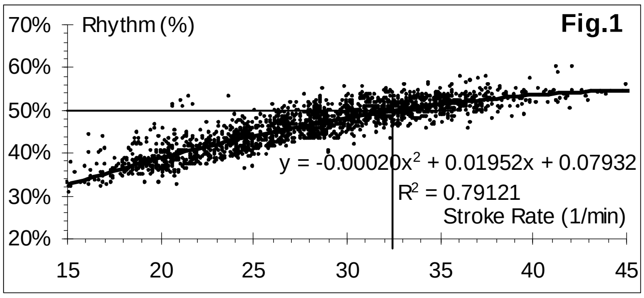
Imagine two connected ergs on slides (Fig.2). A rower sits on one of them, but the seat of another erg is occupied by a box, which mass is similar to the rower's mass. The box is connected to the handle of the erg. When the rower starts the drive and pushes the stretcher, this force ***Fs*** moves both ergs backwards. It creates reaction force of inertia at the box, which pulls the handle, increases the distance L between the box and erg and rotates flywheel. So, the box produces some erg "score", which is explained by force/power transfer from the rower through the ergs.

Is this effect is negative and should be avoided? Not necessary. **The power transferred from bow rower to the blade of the stern rower could help to keep the boat straight in pairs and fours** (RBN 2008/01). The only problem for the bow rower is lower measured force and power. Therefore, the method 3 with power detection at the stretcher (RBN 2004/06) should be used for accurate rower's testing.

Acknowledgment: Thanks to Eskild Ebbesen and Danish Rowing Federation for kind support of this study.

Rowing rhythm, stroke length and effectiveness

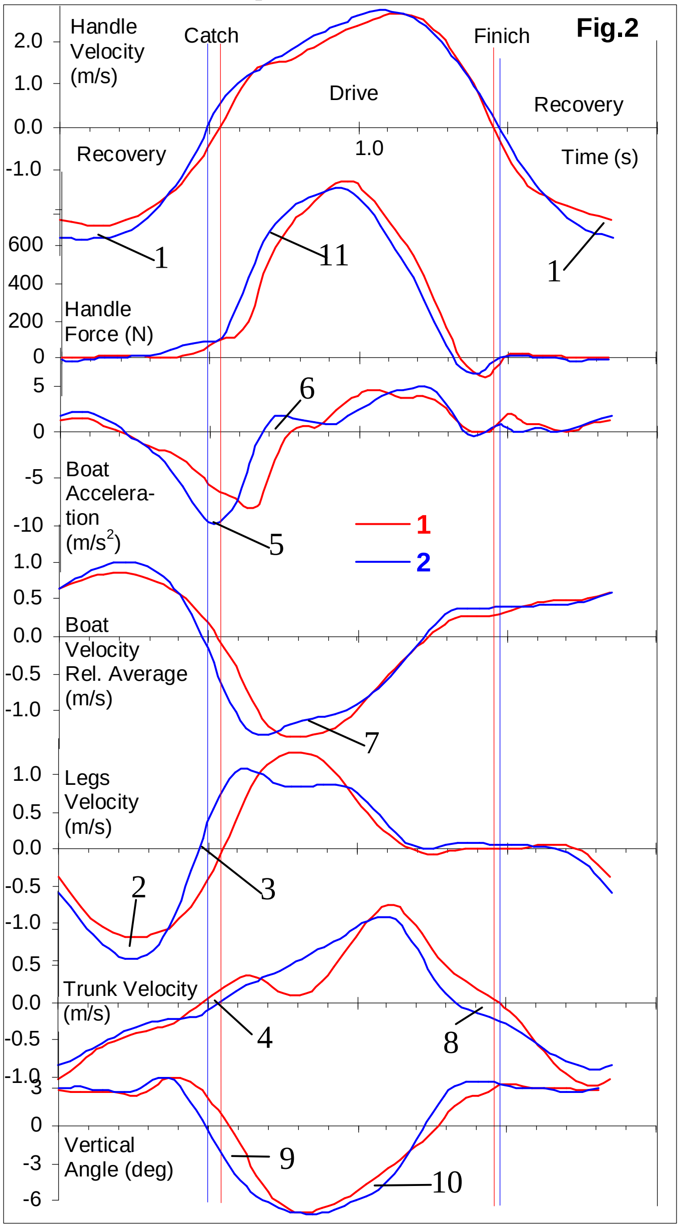
We have briefly discussed time variables of the stroke cycle: times of the drive and recovery, and rhythm (RBN 2003/03). Let's remember that the definition of rhythm is the ratio of the drive time to the total time of the stroke cycle (50% means a 1/1 ratio of the drive to recovery times). It was found that the rhythm has a strong positive correlation (r=0.89) with the stroke rate because possibilities to shorten the drive are limited. However, the stroke rate only explains 79% of the rhythm variation (Fig.1) and 21% depends on other factors.



The standard deviation of residuals from the trend (n=2881) was σ=2.5%, which means that at the same stroke rate the rhythm may vary within ±7.5% (±3σ) in various crews. E.g., at the stroke rate 32.5 str/min the average rhythm based on the above trend is 50%, but it could be between 42.5% and 57.5%.

What other factors affect the rhythm and **is it better to have the rowing rhythm higher or lower?** Many coaches believe that a lower rhythm is more efficient and ask their crews to shorten the drive time, but does that make sense? To answer, we analysed biomechanical variables of two M1x at the same stroke rate 32.5 str/min (Fig.2). Sculler 1 (red) had a rhythm of 49.5% or 0.91s drive time compared to sculler 2's (blue) 52.5% and 0.97s correspondingly; i.e. the last one had a 3% higher rhythm and 0.06s longer drive time. The reason for this difference was quite simple: sculler 1 had a total oar angle of 107.5 deg, while sculler 2 had 116 deg; i.e. he had an 8.5 deg longer stroke length. This reason fully explains the difference in rhythm and drive time since the average handle velocity during the drive (= drive length / time) had the same value of 1.73 m/s in both scullers. This happened in spite of sculler 1 applying a 3.9% higher maximal force and 2.6% higher average force than sculler 2.

What other biomechanical features are related to this difference in rhythm and stroke length? During the recovery, sculler 2 has to move the handle much faster (Fig.2, 1) to cover a longer distance in a shorter time, so his average handle speed was 11.7% higher. This was impossible without faster seat/leg movement (2). At the catch, sculler 2 changes direction of the seat movement much quicker than sculler 1, slightly before his handles change direction (3). Contrarily, sculler 1 uses his trunk even before the catch (4). Consequently, the boat acceleration of sculler 2 has an earlier and deeper negative peak (5), but higher first positive peak (6), so his boat and stretcher move relatively faster (7), creating a better platform for acceleration of sculler's 2 mass ("trampoline effect", RBN 2006.02).



Other technical advantages of sculler 2 were:

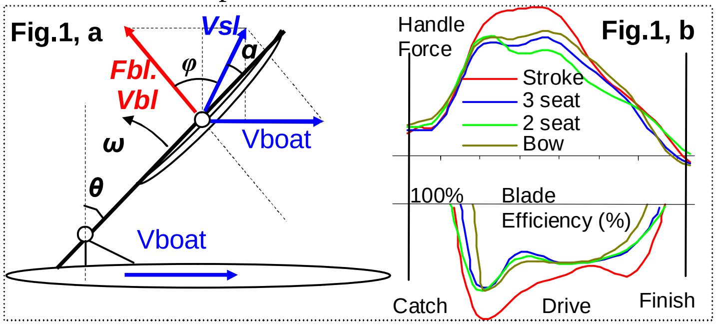
- More effective return of the trunk at the finish (8);
- Better blade work at the catch (9) and finish (10);
- Faster force increase up to 70% of max. (11);
- 1.5% lower variation of the boat speed (0.5s gain over 2k);
- 3.3% higher rowing power because of longer drive.

As a result, the boat speed of sculler 2 was 5.9% higher (6:34 for 2k) than sculler 1 (6:57) as well as his performance (Worlds medallist compared to third finalist for sculler 1).

Conclusion: **The rhythm and drive time can not be changed voluntary as they depend on the stroke rate, length and boat speed. The stroke length should be maintained as the first priority.** There are other factors, which may affect rhythm (shape of the force curve and depth of the blade) which we may study in the future.

Blade propulsive efficiency and effectiveness

We've already touched on the subject of blade propulsive efficiency before (1, 3, RBN 2007/12) and will discuss further now: what it means, how it can be evaluated and improved.



Let's remember that the blade efficiency ***Ebl*** was derived as a ratio of powers (Fig.1, a):

Ebl = (Ptot – Pw) / Ptot ***(1)***

Where ***Ptot*** is the total power production of the rower, ***Pw*** is waste power spent on moving the water at the blade. These instantaneous powers were derived as:

Ptot = Fbl Vbl ***(2)***

Where ***Fbl*** is blade force, ***Vbl*** is blade velocity relative the boat reference frame, and

Pw = Fbl Vsl cosφ ***(3)***

Where ***Vsl*** velocity of the blade slippage relative to the water, ***φ*** is the angle between vectors of this velocity and blade force ***Fbl***. Angle ***φ*** is the reversed angle of attack ***a*** (assuming the blade force is perpendicular to its surface), so:

cos φ = cos(90 - a) = sin a ***(4)***

Combining equations 1 - 4 and moving ***Fbl*** out of brackets, we get:

Ebl = (Vbl–Vsl sin a)/Vbl = 1–(Vsl sin a)/Vbl ***(5)***

Then, we use a general equation of the drag force:

$$Fbl = k\,\rho\,A\,Vsl^2 \quad (6)$$

Where ***ρ*** is water density, ***A*** is the area of the blade, ***k*** is the combined drag factor of the blade, which depends on blade shape and angle of attack (the last defines a ratio of the lift and drag factors, see 2). So, the blade slippage ***Vsl*** can be defined as:

$$Vsl = (Fbl / (k\,\rho\,A))^{0.5} \quad (7)$$

Substituting ***Vsl*** in the equation 5, we get:

$$Ebl = 1-((Fbl / (k\,\rho\,A))^{0.5} \sin a) / Vbl =$$
$$= 1 - \sin a / (k\,\rho\,A)^{0.5} * Fbl^{0.5} / Vbl \quad (8)$$

This equation can be useful to answer the question: **<u>What factors affect the blade propulsive efficiency?</u>**

1. The blade efficiency is higher, when the angle of attack is sharper (***sin a*** is lower). At ***a=0*** (the blade velocity is parallel to its axis) the blade is absolutely efficient (***Ebl=100%)***. This effect can be called "an ideal hydro lift", when the vectors of force and velocity at the blade are perpendicular and drag and energy losses are zero.
2. The blade efficiency is higher, when any of the multipliers ***k ρ A*** increase: the blade shape is more efficient (***k***↑), and/or the water is more dense (***ρ***↑), and/or the blade area is bigger (***A***↑).
3. The blade efficiency is higher, when ratio $Fbl^{0.5}/Vbl$ became lower, i.e. the blade force decreases, but blade velocity increases. This usually happens at the end of the drive (Fig.1, b), which explains the rise of the efficiency curve. The efficiency is 100%, when blade force is zero, i.e. the rower does not pull at all, but the blade still moves in the water. When the blade force is negative (***Fbl<0)***, the blade efficiency can not be defined with the equation 8. However, from the equation 1, ***Ebl*** can be higher than 100%, if ***Pw*** is negative. This means that the energy is not spent on the moving the water at the blade, but it is taken from it and added to the total power of a rower, i.e. when the rower takes the run off.

The first two points above could be used to decrease the amount of energy wasted to slippage of the blade, though the water density is given by conditions and chances to improve the angle of attack, blade shape and area are quite limited. The 3rd point is quite controversial:

- The ratio of the blade force and velocity can be changed with gearing: say, at two times longer outboard and the same inboard, the blade force is decreased twice, but its velocity is increased by the same factor. However, the force in equation 8 is in square root, so the ratio $Fbl^{0.5}/Vbl$ decreases, which explains why **<u>the blade efficiency is higher with heavier gearing</u>** (RBN 2011/09).
- At the same blade slip ***Vsl***, its velocity ***Vbl*** (relative to the boat) is directly proportional to the boat velocity ***Vboat***. This explains why **<u>the blade efficiency appeared to be higher in faster / bigger boats</u>** (3), though the real slippage of the blade could be the same.
- Increasing the blade efficiency by means of decreasing the blade force does not make sense, because it decreases the total and propulsive power – the main objective in rowing. **<u>In a crew, the strongest rower usually has the lowest blade efficiency and vice versa</u>** (Fig.1, b). Therefore, a correlation between average force and blade efficiency within a crew is negative (r = -0.48).

Concluding: In its current definition, **<u>the blade propulsive efficiency can be used for limited evaluation of the equipment qualities and rower's oar handling skills, but only at a constant blade force and velocity.</u>** Another measure should be found for evaluation of combined effectiveness of the blade work.

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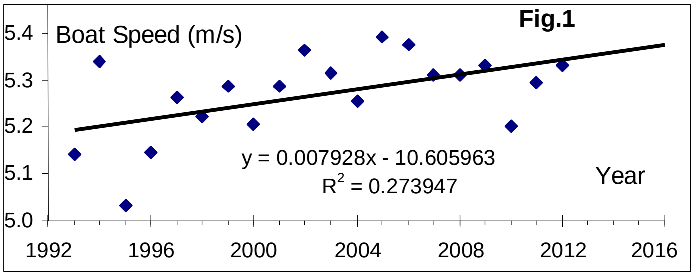
Race analysis after Olympics-2012

As usual, after four years of the Olympic cycle we analysed performances in World rowing regattas.

- To define general boat speed trends, we used a different method compared to previous publications, where speed was analysed based on winners and finalists of the world championships and Olympics. In, fact the World Best Times (WBT) were not always shown in the finals, which we saw this year: six WBT were set during the heats of the World cup in Lucerne and one in London 2012. Therefore, we used a different approach: the Best Times of the Year (BTY) were derived from the past 20 years 1993-2012 (Before 2000 the data was only available for World regatta finals).

It was found that the trend of average boat speed in 14 Olympic events grew by 0.79% per year (Fig.1). The time factor explains 27% of the performance variability and the rest is explained by other factors, mainly by weather conditions.



Using the trends in each event, we derived "Gold Times" for the year 2016 (GT2016) using the following method: if the statistical value was better than WBT, the first one was used; otherwise the value in the middle between it and WBT was used. The last column "New WBT" in the following table shows the year, when the new WBT is expected based on the current trend of BTY:

Event	WBT	WBT year	Growth	GT2016	New WBT
M8+	5:19.35	2012	1.89%	**5:19.5**	2017
LM4-	5:45.60	1999	1.87%	**5:45.7**	2016
M4x	5:33.15	2012	1.84%	**5:34.0**	2019
LW2x	6:49.43	2012	1.55%	**6:48.2**	2015
W8+	5:54.17	2012	1.51%	**5:54.2**	2016
W4x	6:09.38	2012	1.16%	**6:11.1**	2024
LM2x	6:10.02	2007	1.13%	**6:09.6**	2015
M2-	6:08.50	2012	0.78%	**6:10.8**	2024
M4-	5:37.86	2012	0.54%	**5:41.0**	2029
W2x	6:38.78	2002	0.30%	**6:41.1**	2027
W1x	7:07.71	2002	0.26%	**7:11.6**	2038
W2-	6:53.80	2002	0.24%	**6:55.1**	2021
M2x	6:03.25	2006	0.22%	**6:05.4**	2029
M1x	6:33.35	2009	0.19%	**6:34.4**	2020

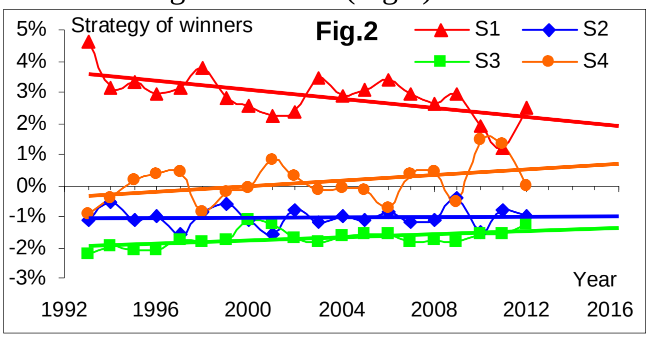
The lowest growth of 0.2-0.3% per year was found in M1x, M2x, W2-, W1x and W2x, i.e. in small boats (SB), in the open category; except M2-. The longest "waiting period" of 10-26 years till new WBT is expected here. The future will show us, if this is evidence of achieving the limit of performance, or whether it's just a temporary stagnation related to the current generation of athletes, coaches and training technologies?

Conversely, **trends in lightweights (LW) and big boats (BB) show quite a high growth 1.1-1.9% per year**, so we can expect significant progress in these events. Here we observed a much tougher competition for medals in London-2012, where average margins within medallists were 2.3s in LW and 3.1 in BB, compare to 5.4s in small boats. We can only speculate that the progress in LW is related to a wider selection of athletes of average size. In BB, the likely reason is the rise in centralized professional systems of athlete's development in many leading rowing nations, which facilitates the matching of better rowers for longer periods of time and achieving better training and synchronisation in the crew. We would be very grateful for your ideas in this area.

- Unfortunately, GPS data was not available for the London-2012 Olympic regatta due to IOC ownership of the results. We hope, it'll be published soon and suitable for analysis of stroke rates.
- In RBN 2008/09 we predicted the average race strategy of the winners in 2012: +2.5%, -1.1%, -1.4%, +0.2%. The winners of London-2012 expectedly showed the strategy of +2.5%, -1.0%, -1.3%, 0.0% on average, which is very close to our forecast.

OG2016	Gold	Silver	Bronze	4th	5th	6th
Start	2.5%	2.2%	2.5%	1.9%	2.5%	2.9%
2nd 500	-1.0%	-1.3%	-0.8%	-1.1%	-0.8%	-0.9%
3rd 500	-1.3%	-1.4%	-1.5%	-0.8%	-1.6%	-1.6%
Finish	0.0%	0.6%	0.0%	0.2%	0.0%	-0.1%

The table shows that there is no significant difference between the finalists: the winners, bronze medallists and 5th place takers used very similar race strategies. This suggests that **now the races were won because of proportionally faster boat speeds in all sections of the race** and most of competitors' strategies are close to the general trend (Fig.2).



From the current trends we can forecast the following typical strategy of the winners for 2016: +1.9%, -1.0%, -1.4%, +0.7%. Which means **the boat speed during the race is becoming more and more even**.

Dynamic analysis in transverse (horizontal) plane

When a rower pulls the handle in a boat, the force is usually applied not exactly at the perpendicular direction to the oar shaft. This is one of the differences between on-water rowing and an erg, where the force is always perpendicular to the axis of the handle. In rowing, at the catch, the angle between the oar and outside forearm is about 70°, and for inside arm it is 60° (Fig.1), so the line of the resultant force should be directed at the angle 66-68° (outside arm pulls higher force). In sculling, the angle between the oar and forearm is sharper: at the catch it is about 60° (Fig.2).

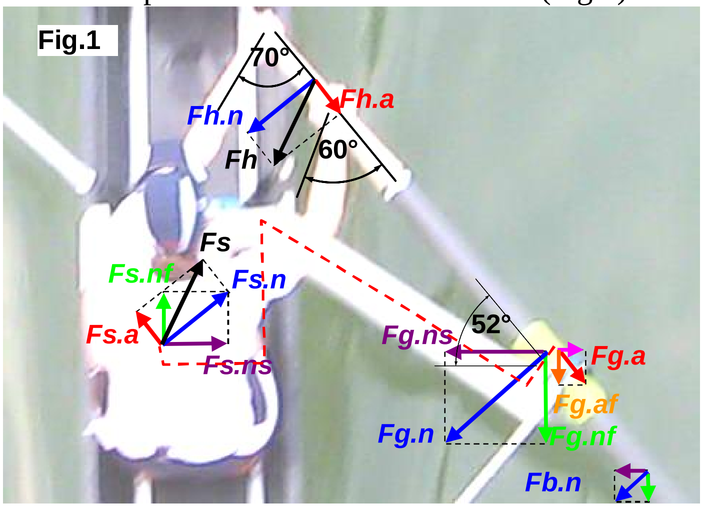


Fig.1

The resultant handle force ***Fh*** can be broken down into two components: a normal (perpendicular) force ***Fh.n*** and an axial force ***Fh.a***. At the pulling angle A=60° the normal component ***Fh.n*** should be equal to sin(A)=86.7% of the total force ***Fh***, and the axial component ***Fh.a***=cos(A)=50% of ***Fh***.

When the axial component ***Fh.a*** is transferred through the oar shaft to the gate, it creates the same axial gate force ***Fg.a*** (ignoring a small axial force of hydrodynamic resistance from the blade). On the other side, to create the axial handle force, the rower has to apply a force at the stretcher of the same magnitude, but in opposite direction. As the stretcher is connected to the pin-gate through the rigger, these forces cancel themselves, i.e. they are internal forces and **the axial handle force does not contribute to the propulsion of the rower-boat system**. It does not create any power and energy losses, because there is no movement of the oar relative to the boat in this direction, but **works like a heavier gearing**: the total force is higher (by 13.3% at A=60°), but slower by the same factor.

The normal handle force ***Fh.n*** is also transferred to the gate, where it is summed up with the normal blade force ***Fb.n***, which is created by reaction of the water. Therefore, the normal gate force ***Fg.n*** is higher than the handle force:

$$Fg.n = Fh.n + Fb.n = Fh.n\ Lout.a / (Lout.a + Lin.a) \qquad (1)$$

where ***Lin.a*** is actual inboard length, ***Lout.a*** - actual outboard. The normal gate force can be decomposed into forward ***Fg.nf*** and side ***Fg.ns*** components. On other side, the handle force creates an opposite reaction force ***Fs*** applied to the system through the rower's body. Its axial component ***Fs.a*** is balanced at the gate, but the normal component ***Fs.n*** can be broken down into forward ***Fs.nf*** and side ***Fs.ns*** forces. As the forward gate force ***Fg.nf*** is higher than the handle reaction force ***Fs.nf***, the difference between them makes a propulsive force, which is transferred from the blade in this way and accelerates the rower-boat system forward. Only the normal force ***Fh.n*** rotates the oar around the pin and creates velocity in this direction. A product of these force and velocity is the handle power, which is transferred through the leverage of the oar, applied by the blade to the water and spent on the propulsion of the rower-boat system and waste power of the blade "slippage" in the water (RBN 2007/12, 2012/06). Concluding: **Only normal handle force creates the propulsion of the system**.

When the force is measured at the pin in the forward direction only, the output is a combination of the normal-propulsive ***Fg.nf*** plus axial-parasite ***Fg.af*** components, so it is not possible to split them. Therefore, the pin force must be measured in two dimensions and the normal to the oar component must be derived using the oar-gate angle. Measurement at the gate is easier, as it detects the normal component directly (RBN 2010/03).

In sculling, the side components of two handle forces cancel themselves in the rower's body (Fig.2). Therefore, the resultant force has no side components and applied in the direction parallel to the boat. This could be a reason why the forces in sculling are higher than in rowing (RBN 2010/08) and similar boats are faster in sculling.

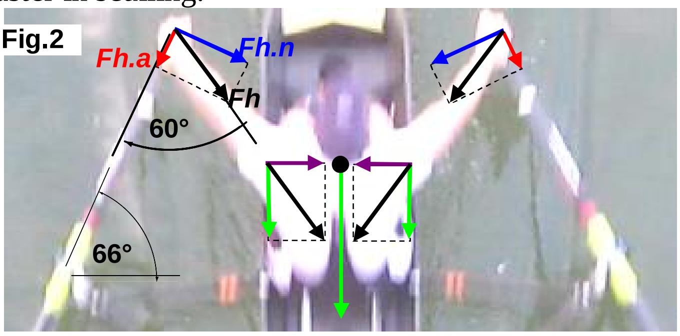


Fig.2

Fig. 3 shows the normal and axial forces in LM1x at 33 str/min measured with 2D instrumented gates (**BioRowTel**, http://www.biorow.com/PS_tel_files/BioRowTel%20Gate%202012.pdf)

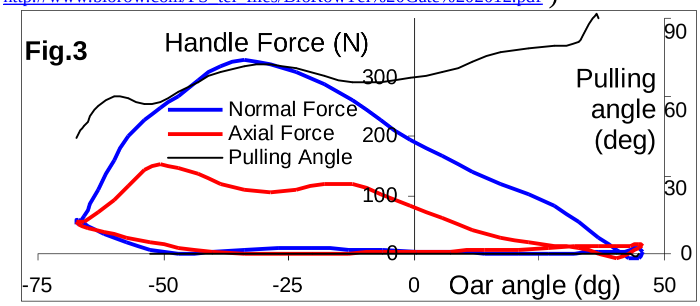


Fig.3

The pulling angle (between the resultant force and the oar shaft) derived from the ratio of the forces achieves 90° only at the very end of the drive.

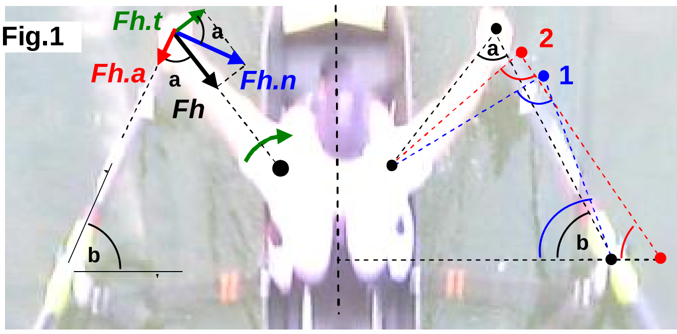
Concluding: **A rower should maximise the normal handle force applying minimal axial force to keep the oar in the gate.**

Dynamic analysis in horizontal plane. Part II.

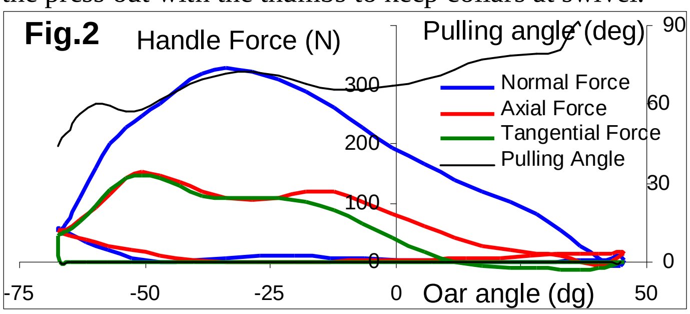
We received very positive feedback on our previous Newsletter and continue discussing forces in the horizontal plain. Stephen Aitken, a coach at TSS club, asked: **could scullers use their pectorals at the catch** to increase the normal component of the handle force?

Yes, in sculling, bringing the arm together at the beginning of the drive, i.e. applying some inwards torque at the shoulder using pectorals muscles could be useful. This torque creates a tangential force at the handle ***Fh.t*** in the perpendicular direction to the arm (Fig.1). To make the resultant force perpendicular to oar, ***Fh.t*** must have the following proportion to the pulling force ***Fh*** and angle ***a***:

Fh.p = Fh / tan(a) ***(1)***



The Fig.2 shows that amount of the tangential force ***Fh.t***, which is required to make the pulling angle straight and completely eliminate the axial force ***Fh.a***. The data from the previous Newsletter was used of the same LM1x at 33 str/min. It can be seen, that hypothetical ***Fh.t*** is very close to measured axial force ***Fh.a*** and must be very significant, up to 150N. It is unlikely that pectorals of this lightweight sculler are able to produce enough torque to create this force at very long lever of the straight arm. However, it is possible to achieve a partial effect and make the resultant vector of the handle force closer to the perpendicular. At the pulling angles a=60-90° the tangential force ***Fh.t*** is nearly reversely proportional to the axial force ***Fh.a***, because cos(a)≈1/tan(a), so, the more tangential force is produced with pectorals, the less axial force is applied to the oar. The negative tangential force towards the finish shows the press out with the thumbs to keep collars at swivel.

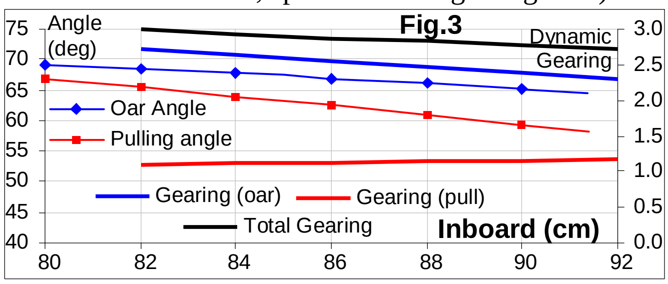


Strength developments of the pectorals, say bench press exercise, could be useful for scullers, but not for rowers, where pectorals can not be utilised there in this way and core muscles should be used instead. It is still not clear if using pectorals would increase a general efficiency and effectiveness in sculling, so more experimenting needed with measurements of energy consumption (VO_2) and muscles coordination (EMG).

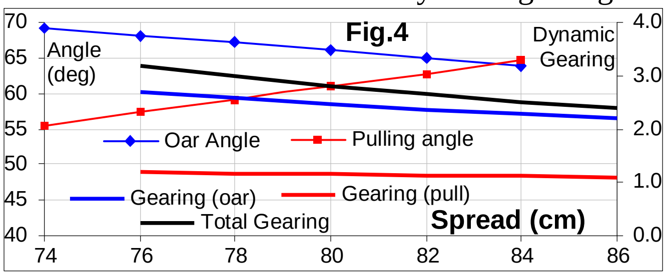
How can we adjust rigging to make the pulling angle straighter and reduce the axial handle force?

Longer arms and wider shoulders of a sculler make pulling angle ***a*** more acute and increase the oar angle ***b***, which both make "dynamic gearing" heavier. Therefore, the arms span (sum of the shoulder width and arms length) should be taken into account for rigging adjustment. In rowing, arms span has no such effect.

With shorter inboard (Fig.1, 1), the position of the handle moves outwards, which makes the pulling angle ***a*** straighter and dynamic gearing lighter. However, it increases the oar angle ***b*** and dynamic gearing of the oar becomes "heavier" (2007/03), which overcomes the effect of "lighter gearing" of the pulling angle. Fig.3 shows dependence of the pulling and oar angles and corresponding dynamic gearing on the inboard length (assuming constant position of the shoulder, spread and oar gearing ratio).



Wider span/spread (Fig.1, 2) makes the pulling angle ***a*** straighter and also decreases the oar angle ***b***, which we already mentioned in RBN 2007/02. This means that both trends have the same direction and enhance each other effect on the dynamic gearing:



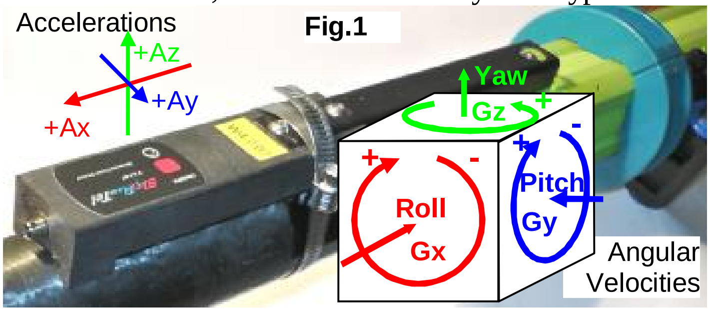
This makes the effect of the spread very noticeable: **<u>wider spread makes dynamic gearing significantly lighter in both rowing and sculling</u>**. This could be a reason why, historically, the ratio of the outboard to the spread was used as a measure of gearing ratio. However, it works only at the catch and beginning of the drive. At the middle of the drive and at finish, the spread do not really affect the oar and pulling angles, so and the dynamic gearing. Therefore, **<u>the only direct and valid measure of the oar gearing *G* is the ratio of actual outboard *Out* to inboard *In*</u>**:

G = Out / In ***(2)***

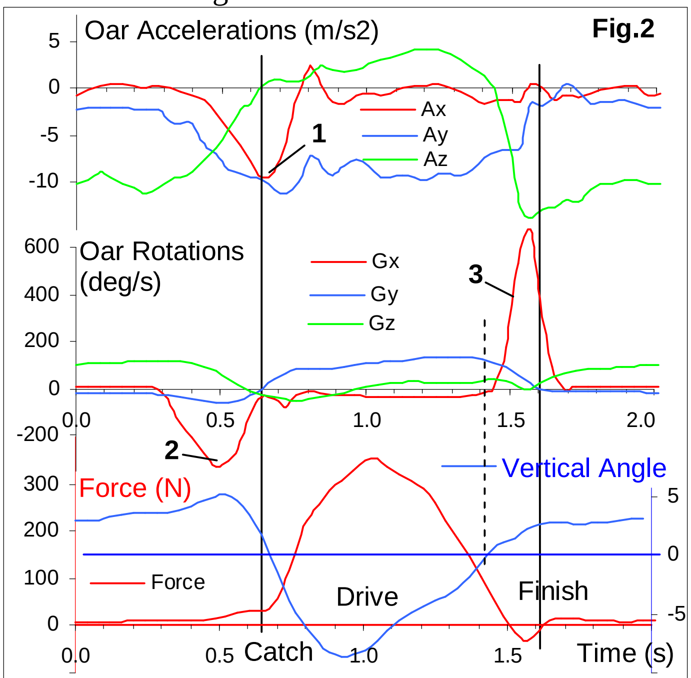
All other rigging variables, such as spread and position of the stretcher (affects oar angles) could be considered as indirect factors, which have effect at various parts of the drive, so we call them "dynamic gearing".

Rotational motions of the oar.

In October we have obtained the first data of the rotational motions of the oar measured with a new ***BioRow 7D*** wireless sensor. The sensor was mounted on the inboard near the button (Fig.1) and was capable of measuring the handle force (in similar way with the standard wired handle force sensor) as well as 3D accelerations and 3D oar rotations. The data through BlueTooth is transmitted to the Master unit of ***BioRowTel*** system, which can handle up to 8 sensors at the same time, so it works with any boat type.

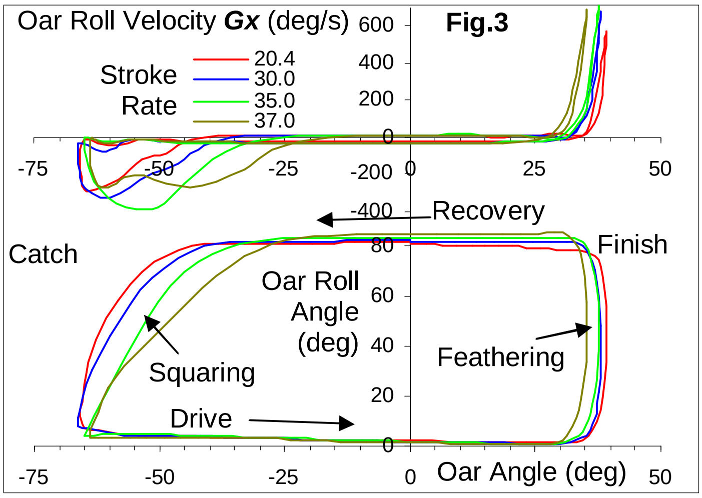


The frame of reference was set similarly to the boat motions analysis (RBN 2012/03) and the axes directions were defined by the design of the sensor. Fig.2 shows the oar accelerations and angular velocities together with the handle force and oar vertical angle obtained from the right oar in M1x at 30 str/min:



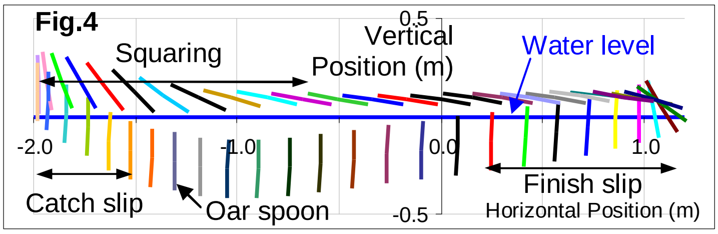
During the drive, the sensor is positioned underneath the oar upside down compared to the position on Fig.1, so ***Ay*** and ***Gy*** (pitch) are related to the vertical movements of the oar and ***Az*** and ***Gz*** (yaw) – to the horizontal ones. During recovery, the oar is rolled 90^o (feathered), so ***Ay*** and ***Gy*** became horizontal measures and ***Az*** and ***Gz*** – vertical ones. Also, the sensor rotates with the oar in horizontal plane for more than 100^o. At the catch, its ***X*** axis is positioned at about 30^o to the boat axis, so ***Ax*** measures the boat acceleration (Fig.2, 1). At the middle of the drive, the ***X*** axis of the sensor is close to the perpendicular to the boat, so ***Ax*** became very close to zero.

The most understandable and informative measured variable appeared to be the roll ***Gx***, which is clearly related to the squaring-feathering of the oar. Fig.2 shows (2) that the squaring takes about 0.35s and completed at the catch, when the oar change direction, but the blade is still in the air. The feathering in this sculler began, when the centre of the blade crosses the water level (3) and completed in about 0.25s – faster than squaring. Fig.3 shows the oar roll in the same M1x at various stroke rates:



At low rate, the squaring of the blade before catch takes about 15^o of horizontal movement of the oar. At the high rate, the squaring takes about the same time, but twice longer distance up to 40^o, because of much faster horizontal movement of the oar. The feathering distance at the finish is independent on the stroke rate.

The oar roll data in conjunction with horizontal and vertical oar angles allows ***BioRowTel*** software a full reconstruction of the oar movements relative to the water level. Fig.4 shows this reconstruction of the same M1x at the stroke rate 37 str/min:

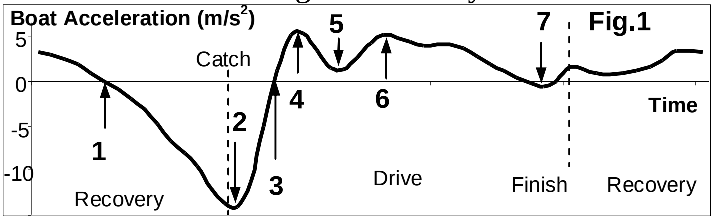


In this sculler, **<u>the blade moves nearly half the distance of the recovery in a semi-squared position, which significantly increases losses on the aerodynamic drag resistance</u>** (RBN 2006/04).

More efforts required to build a mathematical model, which will combine complex data and allows explaining other measured variables. Normative values will be available after enough statistical data gathered. Using **<u>*BioRow 7D* wireless sensor brings very valuable information about oar handling skills in rowing and sculling</u>**.

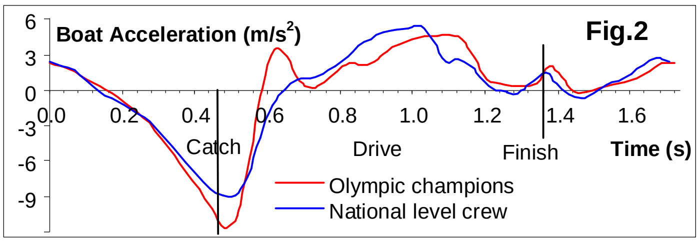
Analysis of 'boat acceleration'

Having briefly touched this topic quite some time ago (RBN 2002/06,08, 2003/11), we will now discus it in more details. Fig.1 represents a typical pattern of boat acceleration during the stroke cycle:



The following variables could be derived, which have specific interpretations in the evaluation of the rowing technique:

1. "***Zero before catch***" defines the moment, when the boat acceleration becomes negative during the recovery. At this moment, the crew changes the force application to the stretcher from pulling to pushing, which influences the deceleration of the seat movement and coincides with the peak leg velocity during the recovery. At high stroke rates and in better crews, this moment occurs later and closer to the catch, so its position relative to the oar angle and timing relative to the catch has a negative correlation with the stroke rate (r = -0.35, see Appendix 1).
2. "***Negative peak***" usually happens just after the catch (when the oar has changed direction), but before full entry of the blade. Its magnitude is highly dependant on the stroke rate (r =-0.82, RBN 2002/08). The best crews show a deeper, but narrower negative peak (Fig.2), which could be explained by a sharper "catch through the stretcher" (RBN 2006/09). Therefore, it is very unproductive to try to minimise this so-called "boat check", which is one of the myths of rowing biomechanics. The negative peak has a slightly lower magnitude in eights, which could be explained by a heavier boat mass with the coxswain, in proportion to the rowers' mass.



3. "***Zero after catch***" occurs, when the boat acceleration becomes positive due to the gate/handle forces increasing faster than the stretcher force. This moment happens earlier in better crews and at higher stroke rates (r = 0.37).
4. "***First peak***" is caused by the fast increasing of the gate/handle forces ("front-loaded" drive) and defines «the initial boat acceleration» micro-phase and "the trampoline effect" (RBN 2006/02). According to our statistics (n=5248), it is not observed in about 30% of crews at 20 str/min and in 6% of crews at 36 str/min, so its magnitude has a moderately positive correlation with the stroke rate (r = 0.41). The best crews usually have a higher first peak, which can be close and even greater than the second peak. No significant difference was found in the values of the first peak between various boat types.
5. "***Drive hump***" is explained by an increase of force on the stretcher during "the main rower's acceleration" micro-phase (1), which is caused by shortening the leverage of the stretcher force rel. hips at the placement of the heels onto the footplate (RBN 2008/07). The best crews manage to maintain the value of the drive hump just above zero. Negative values of this variable are usually related to the hump of the force curve, which could be caused by one or several of the following reasons:

- "Disconnection" of the legs and trunk due to a weak posture of the low back (RBN 2010/02);
- "Double trunk work", where the trunk opens early in the catch, causing a hump in the trunk velocity;
- Sinking the blade too deep into the water, which causes a longer vertical leverage of the handle force relative to the stretcher;
- Too quick an increase of force at the catch: "don't bite-off more than you can chew".

6. "***Second peak***" occurs, when leg velocity and stretcher forces start decreasing, while relatively higher handle/gate forces are maintained by fast movements of the trunk and arms. This causes the deceleration of the rower's CM and transfer of his kinetic energy to the boat mass. The value of the second peak has a small positive correlation with the stroke rate (r = 0.23).
7. "***Finish hump***" is related to the transition phase from the drive to recovery and blade removal from water. In the best crews, this value does not drop below zero, which is achieved by active arm-pull ("finish through the handle", RBN 2006/10) and clean blade work without feathering in the water.

The pattern of the boat acceleration should be considered as a resultant variable, a sort of "indicator" of rowing technique. Therefore, it is not very productive to target the boat acceleration itself, but better to look into the movement of the rower and acceleration of his/her CM. The great Steve Fairbain said in 1930: "**Find out how to use your weight and you will have solved the problem of how to move the boat**".

References

Kleshnev, V. 2010. Boat acceleration, temporal structure of the stroke cycle, and effectiveness in rowing. Journal of Sports Engineering and Technology, 233, 63-73.

Appendix 1. Statistical values of the variables of the boat acceleration

	Variable	Mean (n=5248)	±SD	Correlation with Stroke Rate
Positions from Catch in % of Total Oar Angle	Zero Before Catch (%)	33.5%	8.9%	-0.35
	Negative Peak (%)	1.6%	1.7%	0.06
	Zero after Catch (%)	12.1%	3.7%	0.12
	First Peak (%)	16.8%	6.6%	0.18
	Drive Hump (%)	24.4%	7.2%	0.28
	Second Peak (%)	57.2%	15.6%	-0.07
	Finish Hump (%)	82.0%	24.1%	-0.16
Timing from Catch in % of the Stroke Cycle	Zero Before Catch (%)	-19.4%	5.2%	0.37
	Negative Peak (%)	2.9%	1.9%	0.11
	Zero after Catch (%)	9.7%	2.0%	0.37
	First Peak (%)	11.9%	3.0%	0.40
	Drive Hump (%)	15.8%	3.4%	0.60
	Second Peak (%)	27.6%	5.9%	0.37
	Finish Hump (%)	37.9%	9.8%	0.22
Absolute values (m/s^2)	Negative Peak (m/s^2)	-7.42	2.57	-0.82
	First Peak (m/s^2)	1.65	1.19	0.41
	Drive Hump (m/s^2)	0.50	0.88	0.01
	Second Peak (m/s^2)	3.88	1.19	0.23
	Finish Hump (m/s^2)	0.82	1.55	0.28

Stability and variability of rower's motions

Rowing is a cyclic sport that means it requires repeating a similar cycle of motions many times. Usually, 200-250 stroke cycles is performed to cover the standard racing distance of 2000m. Visually, all strokes look the same and only good experts could see some small differences. Biomechanical equipment allows very accurate measurements of rowing motions and software allows determining how consistent or variable motions of each rower in a crew are.

The simplest measure of consistency is variation of the stroke rate: the higher variability, the lower consistency or stability and vice versa. Usually, a coach sets a task for rowers to row a piece of certain duration at a certain stroke rate. If all stroke periods are recorded, it is possible to derive an average stroke rate ***AV*** over the piece and its standard deviation ***SD***. The common measure of consistency is variation ***VAR*** equal to the ratio of ***SD*** to the average:

VAR = SD / AV ***(1)***

In our ***BioRowTel*** software this operation is performed every time before processing the typical patterns over the sample. Then, the data is filtered and all strokes with duration outside a certain range (usually ±2SD) are rejected to produce reliable average patterns.

International level crews usually maintain variation of the stroke rate within 1%, but beginners could have it up to 4-5%. To convert it in absolute numbers, we can use a statistical rule, saying that 99.7% of the data remains within ±3SD range (assuming the normal distribution). At 32 str/min variation 1% means that practically all strokes are within rates 31-33, but 5% variation means the range 27-37 str/min.

Usually, we analyse arrays of average values of each biomechanical variable (angles, forces, accelerations, etc.), which represent typical patterns (curves) of rowing technique over the sample period. Also, ***BioRowTel*** software allows deriving SD values for each variable at each moment of the stroke cycle, which represents variability of rower's motions.

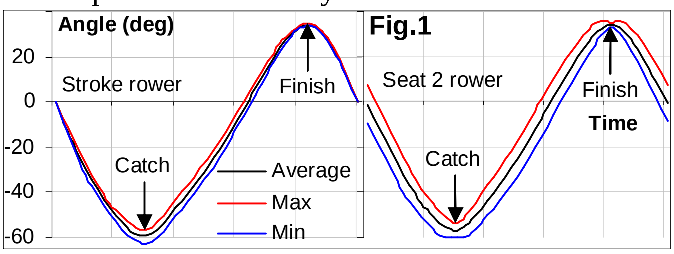
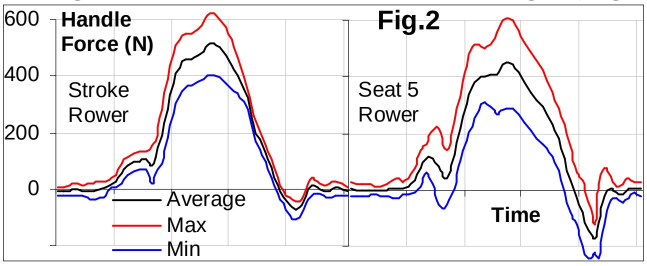


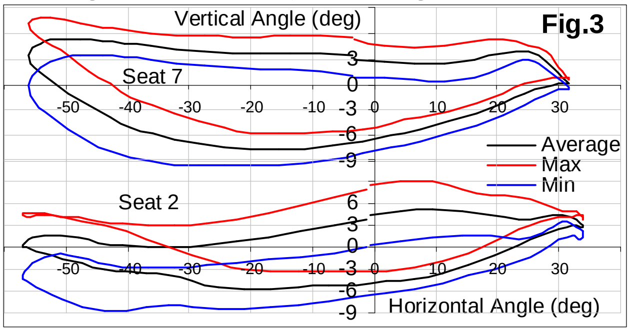
Fig.1 shows average curves of the oar angle and its maximal (+3SD) and minimal (-3SD) curves in two rowers of a collegiate eight at the stroke rate 36 str/min. It was found that stroke rower has the lowest variation in the crew (average SD over stroke cycle is 0.7deg = 0.8% VAR rel. angle amplitude), but the seat 2 rower had the highest variation (SD 2.1deg = 2.3% VAR). At the catch, all rowers had higher variation of the oar angle (average SD = 1.1deg) than at the finish (SD = 0.5deg). This fact illustrates the point that **<u>the catch is more difficult for coordination of rower's motions than finish</u>**, where the oar position is quite firmly defined by rigging and rower's posture.

Variation of the handle force was found to be at a much higher level than it was for the oar angle (Fig.2):

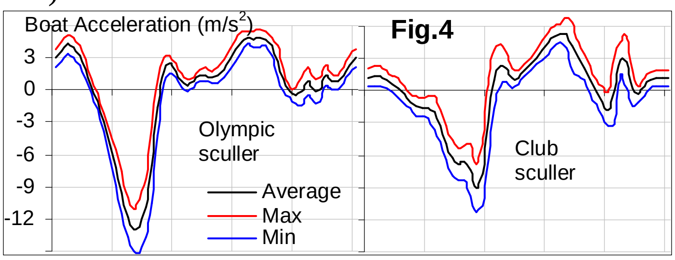


The stroke rower in this crew, also, had the lowest variation of the force in the crew (average SD 16N = 5.7% VAR), the seat 5 had the highest variation (SD 29N = 12.6% VAR). This fact could be explained by the point that **<u>crew rowers have higher complexity of their motions, because they have to coordinate them with the stroke rower</u>**, who set the timing in the crew.

Variation of the vertical angle (Fig.3) was also high, but the stroke rower was not the best here. It was randomly distributed in the crew, where seat 7 had the lowest variation (SD 0.7deg = 5.3% VAR) and seat 2 had the highest variation (SD 1.0deg = 10.1% VAR).



The boat acceleration as a resultant variable (RBN 2012/11) reflects consistency of rowing technique of the whole crew, which was found to be much higher in elite rowers. Fig.4 shows variation of the boat acceleration at 36 str/min in Olympic single (SD 0.31m/s^2 = 1.9% VAR) and in a club sculler (SD 0.59 m/s^2 = 4.1%).



There are many open questions in this area, which require further work: e.g., how to define consistency near zero values of the average, where the variation goes to infinity; normative values and functions.