Rowing Biomechanics

Contents

Rowing

History

Rowing is one of the oldest human activities and known for more than 5,000 years. Rowing in cane boats by means of long oars can be seen on frescoes from the 5th Dynasty of the Pharaohs in Egypt in 2500 B.C. Rowing races in various types of boats were popular in ancient Greece and Rome. Though rowing was not in the program of ancient Olympic Games, there were evidence that more than 100 boats and 1900 oarsmen participated in rowing regattas organized by Emperors Augustus and Claudius (Dal Monte, 1989).

Rowing became popular sport in Europe since the XVII century. The oldest of the currently existing “The boat race” between teams of Oxford and Cambridge Universities began in 1829. In XIX century races of professional scullers collected multi-thousand crows on banks of the Thames River and millions of pounds were spent on betting, which resembles popularity of modern boxing, tennis and Formula-1 car racing.

International Rowing Federation FISA was founded in 1892. FISA is the oldest international sport federation. Now it includes representatives if 118 National rowing associations.

Rowing is the oldest Olympic sport. Though rowing competition was not held on the first Games in Athens in 1896 due to bad weather conditions, it has always been in the program of the modern Olympic Games.

Currently, presence of sports and athletes is limited in Olympic Games. There is very tough competition for a quote. However, rowing managed to maintain the third large quote after athletics and swimming having 14 medals sets and more than 550 athletes participating.

In 2005 adaptive rowing was included in Paralympics, which is also evidence of its growing popularity.

Trends of rowing performance

Long term performance in rowing is difficult to analyse, because it is significantly affected by weather conditions and differences over the courses used during European, World and Olympic events. A more detailed presentation of the progress maybe obtained by comparison of the records from a single regatta and, for that purpose, the Royal Henley Regatta is ideal, because it is the oldest still existing institution in race rowing. It is possible to define the following periods of rowing development, which can be seen on Figure 1:

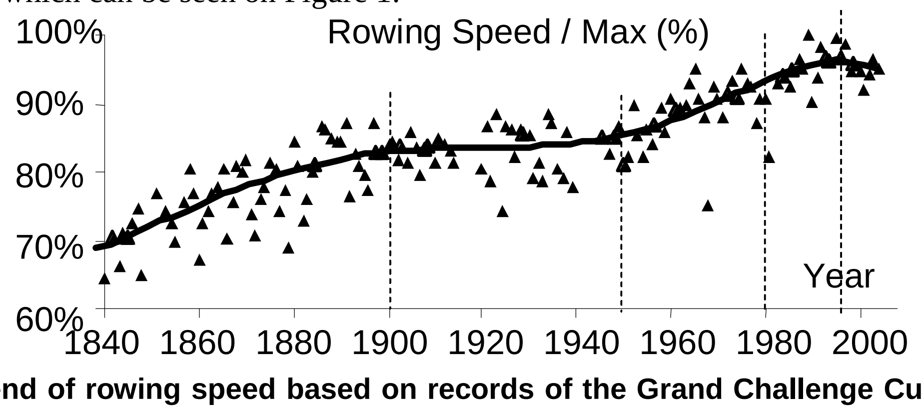


Figure 1. Trend of rowing speed based on records of the Grand Challenge Cup (M8+) of the Royal Henley Regatta

Before 1900 there was a fast growth of performance of 1-1.5% per year, which may be explained by initial development of equipment (timber boats, outriggers, and the sliding seat), in addition to sporting technique and training methods.

The slower growth of ~0.5% per year from 1900 – 1950 may have been caused by the two World Wars, the amateur status of the athletes and the relatively limited competition due to the separation of sport organisations between the East and West political alliances.

However, from 1950 – 1980 performance grew at very fast pace of ~1-2% per year. It can be considered that when Eastern block countries joined Olympic sport in 1952 the competition level was substantially raised. Thus, sport became a political factor and a professional activity, which boomed the training volume, methods and use of drugs in sport. This performance growth was even faster in women, because it coincided with initial development in women's events.

In the period of 1980 – 1996 there has been a slower growth of ~0.5-0.8% a year. This growth rate could be reflective of the training volume approaching its biological limit; an improvement of the drug control. Rowing performance, however, continues to grow relatively faster than in athletics and swimming. We can speculate that the reasons were equipment development (plastic boats and oar s replaced wooden ones, introduction of the "big blade") and active FISA position in wider promoting of rowing and popularisation of modern training technologies.

1996 – now. Stable period and even decreasing of performance. We can speculate that the reasons could be further development of doping control methods (such as blood doping test) and sociological factors.

Boat types and rowers' categories

From its origin up to the 1972 Games rowing had seven male events in Olympic program (1x, 2x, 2-, 2+, 4-, 4+, 8+ on the standard distance 2000 m). In 1976 a number of events was increased to 14: one male event (4x) and six female events (1x, 2x, 4x, 2-, 4-, 8+ on the distance 1000 m) were introduced. Women events changed the distance to the standard 2000m in 1984, which have made female rowing more aerobic with less demand for strength and power. The current Olympic program was introduced after the 1992 Games, when lightweight events were included (LM2x, LM4-, LW2x) on the expense of (M2+, M4+, W4). Yet, these events are included in the World Championships Program. (Table 1)

Table 1. Rowing events in Olympic Games (OG) and World Championships (WC) programs.

Boat Type	Men		Women	
	Heavyweight	Lightweight	Heavyweight	Lightweight
Single scull (1x)	**OG**	WC	**OG**	WC
Double scull (2x)	**OG**	**OG**	**OG**	**OG**
Quad scull (4x)	**OG**	WC	**OG**	WC
Pair (2-)	**OG**	WC	**OG**	
Four (4-)	**OG**	**OG**	WC	
Eight (8+)	**OG**	WC	**OG**	
Pair with coxswain (2+)	WC			
Four with coxswain (4+)	WC			

Rigging

Gearing

In sports such as rowing and cycling the term "gearing" is used for a ratio of the velocities of locomotion to the velocity of athlete action. According to the lever law, the ratio of forces is reversely proportional to the ratio of velocities. Athletes, therefore, have to apply proportionally more force as the gearing decrease velocity of their action at constant speed of locomotion.

In rowing the gearing is defined by two main variables: oar length versus the inboard length (Figure 2).

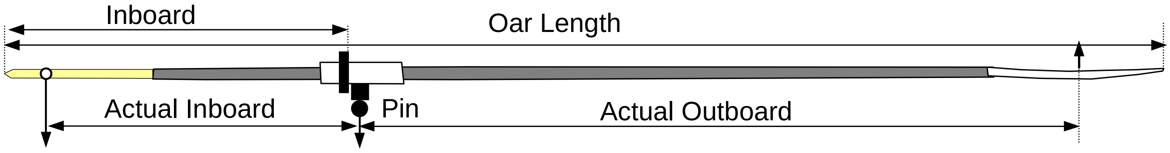


Figure 2. Oar gearing variables

The oar length is measured from the handle top to the outer edge of the blade in the line of the shaft. The inboard is measured from the handle top to the face of button. However, actual resultant forces are applied to different points of the blade:

- Point of the handle force application is difficult to locate exactly and it may vary in different rowers. We assume that the handle force is applied at the centre of the handle, which is located 6 cm from the handle top in sculling and 15 cm – in sweep rowing.
- Gate force applied to the centre of the pin, which offsets from the button on the half width of the gate and it is usually 2cm.
- Blade force applied to the centre of water pressure on the blade. It is even more difficult to define and it may vary depending on the angle of attack. We assume it applied at geometrical centre of the blade, which usually located 20 cm from the outer edge in sculling and 25 cm - in sweep rowing.

Table 2. Oar gearing (based on Nolte, 2005) and corresponding speed characteristics (based on the World best times for 2006) in different boat types

Boat Type	Oar Length (m)	Inboard (m)	Actual Inboard (m)	Actual Outboard (m)	Actual Gearing	Boat speed, men (m/s)	Boat speed, women (m/s)	Handle speed, men (m/s)	Handle speed, women (m/s)
1x	2.88	0.88	0.84	1.78	2.119	5.05	4.68	2.38	2.21
2x	2.88	0.88	0.84	1.78	2.119	5.49	5.02	2.59	2.37
4x	2.89	0.875	0.835	1.795	2.150	5.92	5.39	2.76	2.51
2-	3.72	1.16	1.03	2.29	2.223	5.34	4.83	2.40	2.17
4-	3.73	1.15	1.02	2.31	2.265	5.86		2.59	
8+	3.73	1.14	1.01	2.32	2.297	6.25	5.61	2.72	2.44

Actual gearing is heavier in sculling than in sweep boats. The variation is small between small and big boats and does not correspond to the difference in the speed of the boat. The difference in the handle speeds between 1x/2- and 4x/8+ is quite significant (12-14%). This leads to the variation of the racing rate, which varies from 34-36str/min in 1x/2- to 39-40 str/min in 4x/8+.

Actual gearing is higher (heavier) at the catch and finish of the drive than at the perpendicular position of the oar. At catch and finish the blade moves at the angle to the boat movement and its longitudinal component equal to cosine of the angle. E.g. at the catch angle of 60^o the gearing is two times heavier and at 45^o it is 30% heavier than at the perpendicular oar position.

Rower's workplace

It is important to setup the rower's workplace properly, because its geometry affect vectors of forces and velocities and, hence, efficiency and effectiveness of rowing technique.

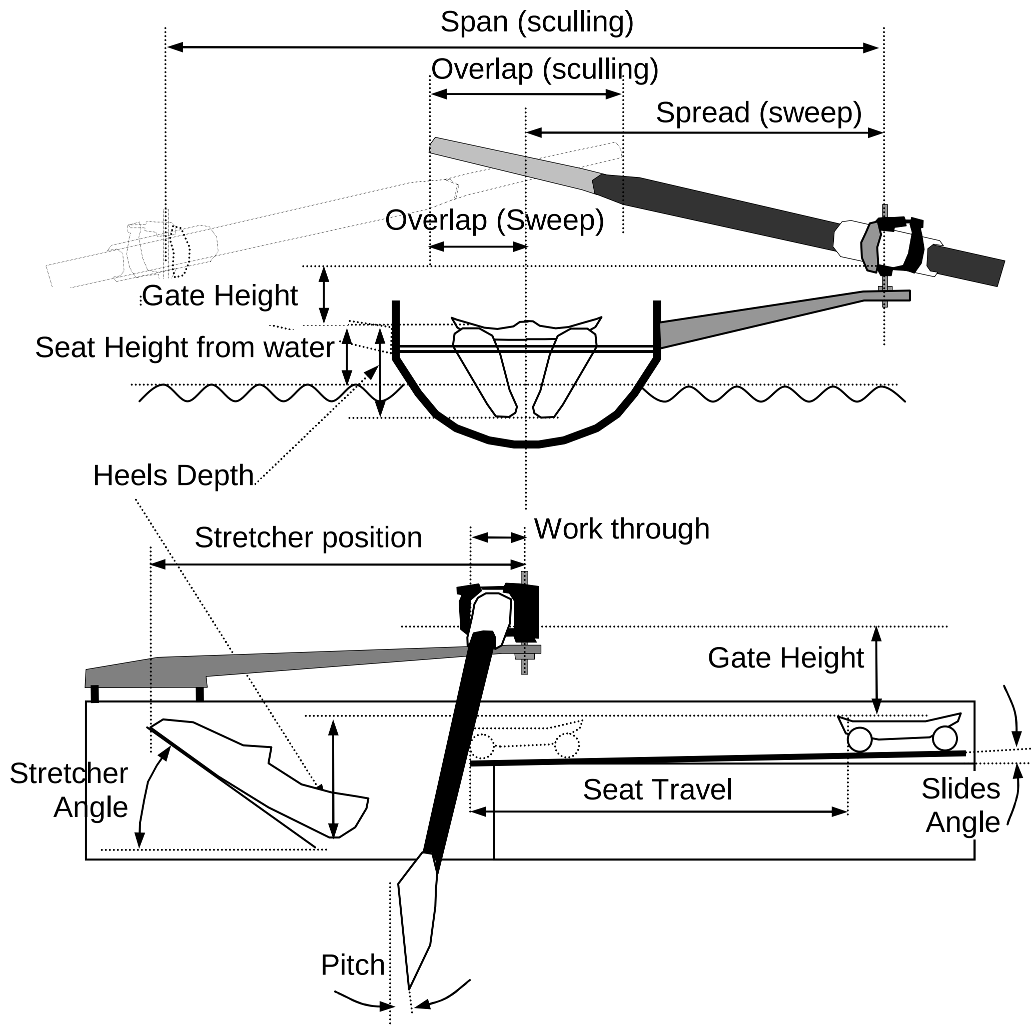


Figure 3. Variables of the rower's workplace geometry

The main variables are:

- Gate height is measured from seat to the bottom of the oarlock and varies from 14 to 19cm depending on the rower's height. In sculling the left gate usually 0.5-2 cm higher than the right one.
- Heels depth is measured from seat to the bottom of the shoes and varies from 15 to 22 cm depending on the rower's body composition.
- Seat height from water varies depending on boat type and weight of the rowers.
- Span in sculling is measured from pin to pin. Spread in sweep rowing is measured from pin to the boat centreline. Usually, the inboard length is longer than the spread in sweep boats or half of the span in sculling boats. This makes overlap measured between tops of the handles in sculling, which is usually 15-20 cm, and between the boat centreline and top of the handle in sweep rowing of 25-30 cm.
- Stretcher position is measured from the pin to the toes of the shoes and is 50-65 cm.
- "Work through" is the distance from the pin to the end of the slides and is 5-12 cm.
- The distance that the seat travels is usually 60-65 cm.
- Stretcher angle varies from 36^o to 45^o.
- Slides angle is usually set between 0.5^o and 1.5^o.
- Oar pitch is the angle between vertical line and the blade. In depends on two settings: pitch of the blade relative to the sleeve and the gate pitch. The first one usually set to zero and the second one varies between 2^o and 6^o. If the pin is leaning inwards, then the pitch at catch will be less and at finish more than it the perpendicular position of the oar. Outwards leaning of

the pin produce the opposite changes in the pitch. Usually, the pin is set vertically, but some coaches use 1^o-2^o outward leaning of the pin, which prevents the blade from going too deep at the catch and too shallow at the finish of the drive.

Mechanics

Propulsion and blade efficiency

When the rower applies force to the oar handle (Fhandle), it is transferred to the blade and applies pressure on the water. According to Newton's 3rd law this creates reaction force on the blade Fr.blade, which is the force that accelerates the rower-boat-oars system (RBOS) forward. During the drive phase, the centre of mass (CM) of the whole system moves forward and the centre of pressure (CP) of the oar slips through the water. Some point on the oar shaft remains stationary and can be considered as an imaginary fulcrum. It is not a real fulcrum because there is no support at this point. The position of the fulcrum changes during the drive phase and depends on the blade propulsive efficiency: the higher the efficiency, the closer fulcrum to the CP of the blade. The fulcrum coincides with CP at 100% efficiency.

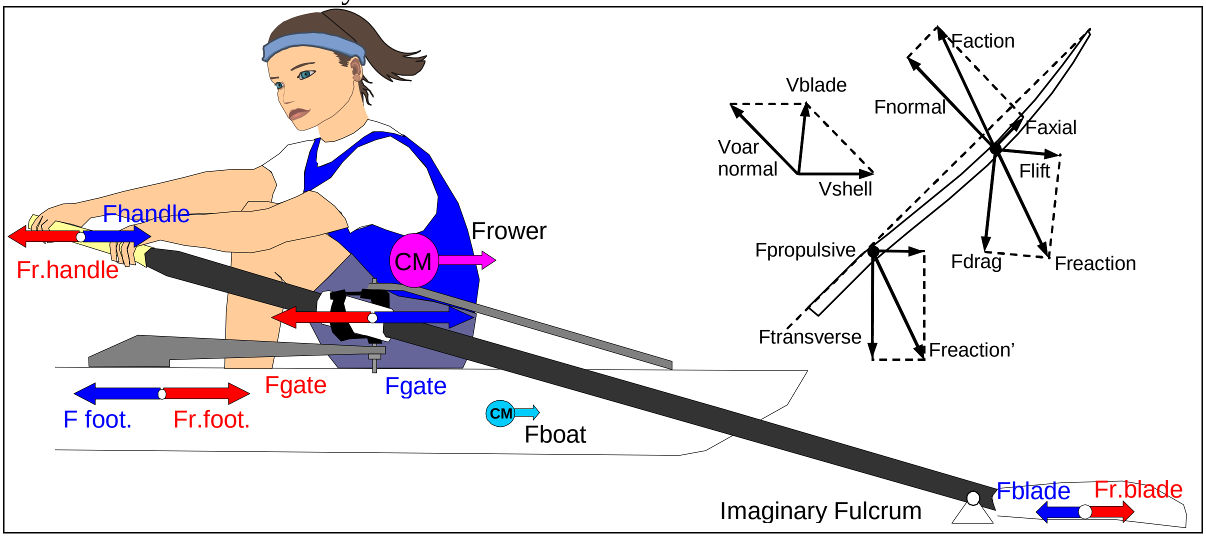


Figure 4. Forces in the rower-boat-oar system

Reaction force on the blade is the sum of the drag and the lift forces. As an angle of attack changes through the drive, the ratio of the drag and lift forces changes from 1:2 the angle 60deg at catch to 1:0 at the oar position perpendicular to the boat (Caplan and Gardner, 2005). The lift force does not result in any loss of energy, i.e. it is 100% efficient, because vectors of force and velocity are perpendicular to each other. The vector of the drag force is parallel to the velocity vector and has opposite direction.

Waste of energy is calculated as a scalar (dot) product of blade force and velocity vectors. Propulsive power is the product of the force and velocity vectors applied to the CM of RBOS. The sum of the propulsive and the waste posers equals the total power applied to the oar handle. Propulsive efficiency of the blade is a ratio of the propulsive power to the total power.

Propulsive efficiency of the blade can be derived by means of measuring instantaneous boat velocity, oar angle and a force at the oar handle or gate (Affeld, 1993, Kleshnev 1999). The force applied to the oar blade (*Fb*) is calculated using measured handle force and oar gearing. The blade velocity (*vb*) is derived using oar angle and boat velocity data.

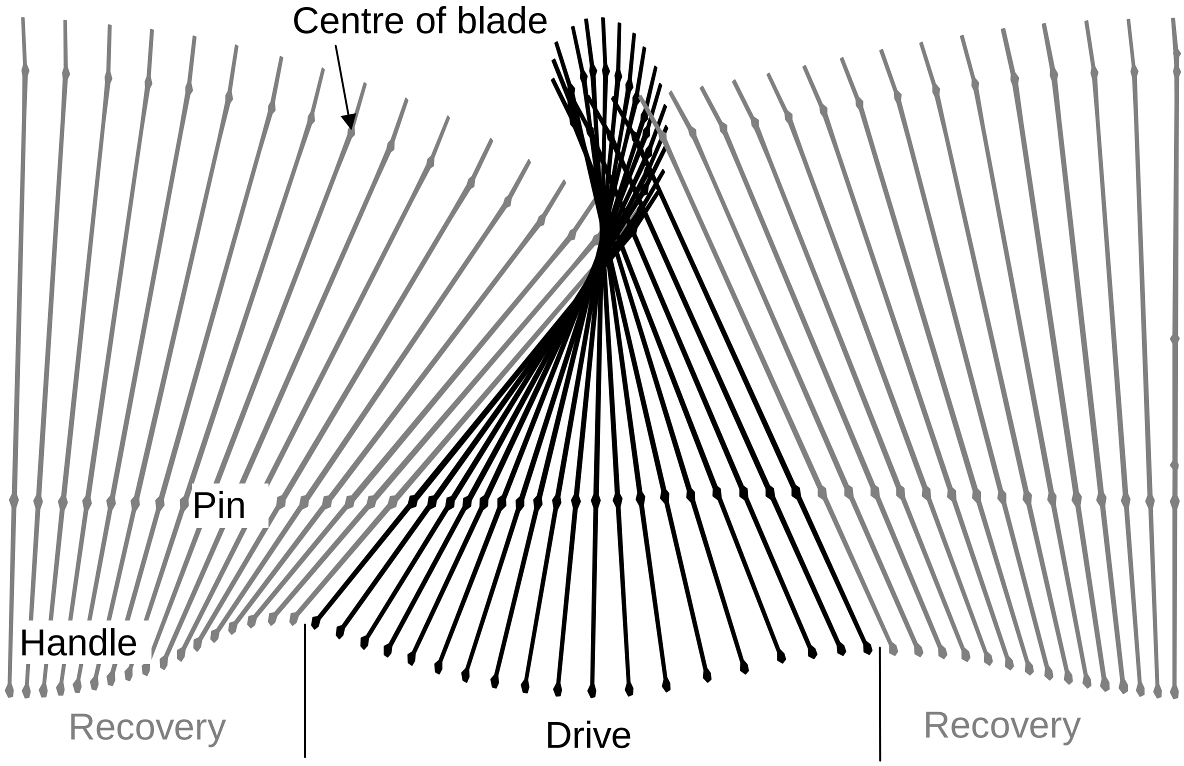


Figure 5. Path of the oar during the stroke cycle

Propulsive efficiency of the blade depends on the relative pressure on the blade, i.e. the ratio of the blade force to the blade area. Lower pressure relates to less slippage of the blade through the water and higher blade propulsive efficiency. To increase efficiency there is a need to reduce blade force or to increase the blade area.

The blade force is reduced at the same handle force by means of changing the oar gearing ratio to heavier values (shorter inboard and longer outboard distance). However, very heavy gearing will decrease muscular efficiency of the rower, because the handle speed will decrease and it makes muscles work in slow static-like regimen.

Increasing of the blade area is also limited because wider blade takes more time and requires more effort for entry and extraction from the water. A very long blade is also inefficient, because it can create counter-movement effect on opposite sides of the blade. Also, the blade efficiency is affected by the velocity of the boat, and it is higher in faster (bigger) boat types.

Sculling has a higher blade efficiency than sweep rowing, which can be explained by higher sum of the blade area. This could be one of the reasons why sculling boat are faster than sweep boats of the same size.

The characteristics of the force application affect blade efficiency and may be controlled by the rower. A force curve with a peak increases blade slippage and decreases efficiency. Conversely, a rectangular shape of the force curve affects efficiency positively. There is a moderate correlation between the ratio of average to maximal force, taken as a measure of the shape of the force curve (100% for rectangle, 50% for triangle), and blade efficiency ($r = 0.48$, $p<0.01$).

Table 3 Average values of the blade propulsive efficiency based on 1470 crew-samples collected during 1998-2005 in the Australian Institute of Sport (AIS).

Table 3. Blade propulsive efficiency in Olympic rowing events

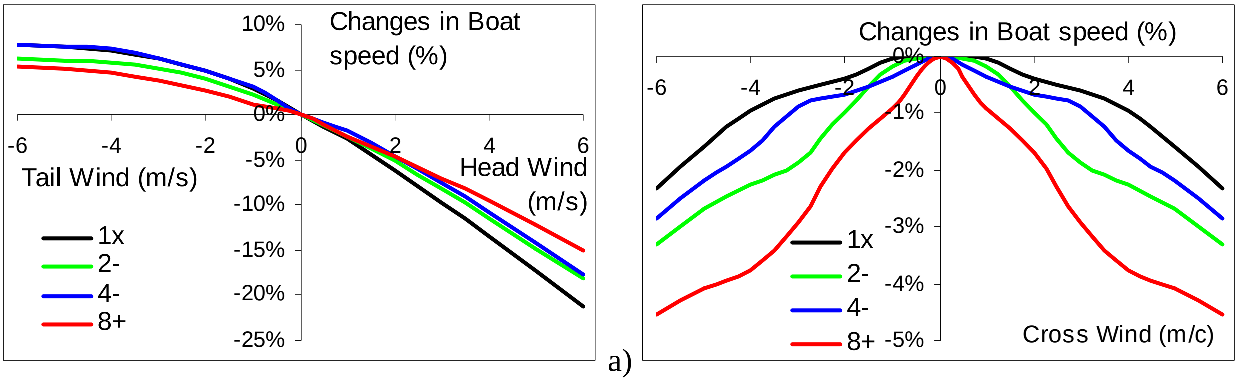
	Men		Woman		Average
Boat Type	Heavy	Light	Heavy	Light	
1x	79.6%		78.5%		79.0%
2-	78.5%		80.6%		79.4%
2x	82.3%	81.9%	83.6%	84.1%	83.0%
4-	80.2%	82.1%	80.5%		81.0%
4x	83.7%		87.3%		85.5%
8-	81.4%		81.5%		81.4%

Bigger boats have higher blade efficiency due to higher average speed, which makes lift force more significant. Scullers are efficient because of the bigger total area of the blade. Higher blade efficiency in lightweight women's crews can be explained by lower force application, which relates to lower relative pressure on the blade and less slippage through the water.

The Vortex Edge blade was introduced in attempt to increase efficiency (Concept 2 web site). The overall improvement of the blade efficiency with Vortex is about 2%. Application of the Vortex shifts the centre of pressure towards the outer edge of the blade, equivalent to increasing the outboard lever of the oar.

Boat Speed: Resistance, Variation, Efficiency

According to fluid dynamics drag resistance force is proportional to the square of boat speed and drag power is proportional to the cube of the velocity. Therefore, if a crew increase the boat speed twice, then they should overcome four times higher drag force and apply eight times more power. Normally, the hydrodynamic resistance of the water represents 85% of the total drag force, which includes 70% water friction, 10% wave resistance and 5% pressure resistance. Aerodynamic resistance normally represents 15%, but at head wind it increases up to 30% at wind speed of 5 m/s and up to 50% of total drag at 10m/s. Correspondingly, in tail wind, air resistance decreases to 0% at wind speed equal to the boat speed. Rowers' bodies create approximately 75% of air resistance, oars give nearly 20%, and the remaining 5% depend on the boat hull and the riggers. Strait head wind is beneficial for big boats, because the bow rower shields the rest of the crew, which decrease the drag. Cross-head wind has less influence on small boats (Figure 6).



a) b)

Figure 6. Boat speed at strait (a) and cross (b) winds (Filter, 2000);

Water viscosity decreases at higher water temperature, which decreases hydrodynamic resistance and allows higher boat speeds

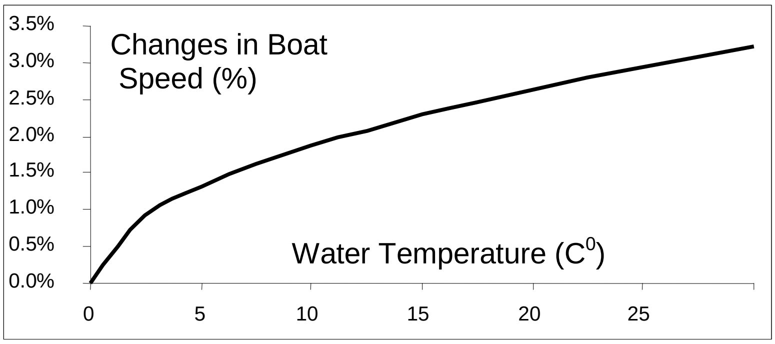
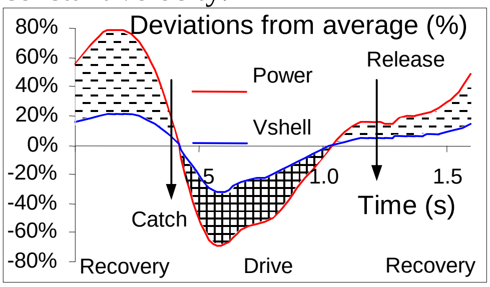
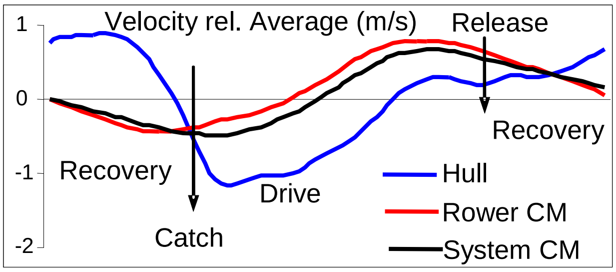


Figure 7. Boat speed at different water temperature (Filter, 2000);

Due to the periodic nature of the drive phase in rowing, the boat speed is not constant during the stroke cycle (Figure 8, a). The drag power increases more at a higher than average boat velocity (dash shaded area on Figure 8, a), than it reduces at a lower than average velocity (cross shaded area). The total energy expenditure at variable boat velocity is, therefore, higher compare with constant velocity.



a)



b)

Figure 8. Deviations of the shell velocity and drag power from average (a);

The ratio of the minimal power required to propel the boat at a given constant speed to the actual propulsive power at variable boat velocity is called "Boat efficiency".

Table 4. Boat Efficiency of rowing in Olympic boat types.

	Men		Woman		Average
Boat Type	Heavy	Light	Heavy	Light	
1x	95.1%		94.5%		94.8%
2-	94.9%		95.1%		95.0%
2x	94.9%	95.5%	95.4%	96.3%	95.5%
4x	96.2%		95.6%		95.9%
4-	95.4%	95.3%	91.9%		94.2%
8+	96.4%		96.5%		96.4%

For improvement of the boat's efficiency Sanderson and Martindale suggested optimisation of the rowers' movement on recovery to maintain the shell speed as constant as possible. In high stroke rates the recovery time is shorter and that dictates faster movement of the rowers' mass and higher acceleration of the shell. Therefore, the boat velocity fluctuations increase with stroke rate (**Error! Reference source not found.**, a), which leads to a decrease of the boat velocity efficiency (**Error! Reference source not found.**, b) and stroke rate has a negative correlation with the boat efficiency ($r = -0.34$, $p < 0.05$). On average, the boat efficiency drops 1.4% from stroke rate 20 (96.0%) to 40 (94.6%).

Table 5. Boat Efficiency of rowing in Olympic boat types.

	Men		Woman		Average
Boat Type	Heavy	Light	Heavy	Light	
1x	95.1%		94.5%		94.8%
2-	94.9%		95.1%		95.0%

2x	94.9%	95.5%	95.4%	96.3%	95.5%
4x	96.2%		95.6%		95.9%
4-	95.4%	95.3%	91.9%		94.2%
8+	96.4%		96.5%		96.4%

Newton's Laws of Motion, Kinetic Energy, Centre of Mass

The implication of Newton's first law is that rowers have to apply force to overcome drag and maintain linear movement of the boat. When force is applied to the blade during the drive phase, an equal and opposite directed reaction force is created, according to the third Newton law. The forward component of this reaction force is the only reason of acceleration of the boat's centre of mass. According to Newton's second law, the magnitude of this acceleration is proportional to the mass of the system and the magnitude of the propulsive force.

When the CM of the boat accelerates, it accumulates kinetic energy, which is spent on overcoming drag resistance and lost as heat to the surroundings of the rowing boat.

However, rowing mechanics is not as simple as it looks. It may appear that the main target of the crew is acceleration of the boat and because the rowers sit in the boat the whole system moves as fast as the boat does. This simplistic observation leads to erroneous coaching theories, which can harm performance in rowing when it is advised to maximise handle-gate force in order to accelerate the boat and at the same time suggesting to minimise the force on the foot stretcher, because it pushes the boat backwards.

The following steps will help to understand the principles of effective rowing technique:

1. To increase the boat speed, rowers have to expend more power to overcome higher drag resistance ($P = kv^3$).
2. The kinetic energy of the whole boat-rower system can be increased (accumulated) only during the drive phase. The increase of the shell's velocity during the recovery is explained by the transfer of the crew's kinetic energy.
3. Because the crew's mass is higher than that of the boat, the crew accumulates 5-6 times more kinetic energy than the boat ($Ek = mv^2/2$). Therefore, the main target for an effective drive phase is to increase the velocity of the crew's centre of mass.
4. The only force accelerating the rower's centre of mass forward is the reaction force on the stretcher. Therefore, maximizing of the stretcher force is the main target of the drive. The handle force pulls the rower backwards.
5. To apply a high stretcher force is not enough for a rower's acceleration. The stretcher must have a supporting connection to the water through the rigger and oar.
6. The stretcher (and the whole shell) has to move fast forwards at the moment of the leg drive.

Thus, rowing can be considered as a series of jumps where each drive phase is a jump and recovery is a flight phase. With this consideration longer jumps or higher jump frequency results in higher rowing speed. The major difference between rowing and real jumping is that rowers have to create support on the stretcher by placing the blade in the water and applying handle force.

Timing of the stroke cycle

Temporal or phase analysis plays an important role in modern sport biomechanics and is the most versatile biomechanical method of analysis across different sports. Other methods based on mechanical parameters (position, velocity, force, etc.) have very different nature in various sport motions. The phase analysis is based on time only and can represent different motions as a sequence of phases and sub-phases.

The accelerations of the boat, rowers' and system centre of mass as well as the oar and seat velocity are used for definition of the micro-phases of the stroke cycle. Figure 10 shows biomechanical parameters of a single sculler obtained during detailed measurements.

Six micro-phases of the drive phase (D1-D6) and three micro-phases of the recovery (R1, R2, R3) are defined in Table 6.

Table 6. Micro-phases and key events of the stroke cycle.

No.	**Key event description**	**Micro-phase** ID	**Micro-phase description**
1	Catch, beginning of the drive. Oar changes direction of movement	**D1. Blade Immersion**	The system's acceleration is still negative. Small inertial forces applied to the handle and the gate, but the foot-stretcher force is already significant. This produces a negative peak of the boat's acceleration and a positive peak of the rower's centre of mass acceleration. Fast increase of handle and legs speed
2	The system's acceleration becomes positive. The centre of the blade crosses the water level	**D2. Initial rowers' acceleration**	Handle force increases, which leads to the gain of the boat's acceleration, but it is still negative and lower than the rowers' centre of mass acceleration.
3	The boat's acceleration become higher than the rowers' centre of mass acceleration. This is caused by the increase of the gate force, which becomes higher than the stretcher force	**D3. Initial boat acceleration**	First positive peak of the boat's acceleration and cavity of the rower's acceleration. The blade is fully immersed. Maximal speed of the legs
4	The boat's acceleration decrease and becomes lower than the rower's acceleration. This is caused by the increase of the stretcher force, which again becomes higher than the gate force	**D4. Rowers' acceleration**	Forces, the rower's and system accelerations increase slowly. Handle speed continues to grow. Legs speed decreases and trunk speed increases
5	The boat's acceleration again becomes higher than the rowers' center of mass acceleration. This is caused by a decrease in the foot-stretcher force, which becomes lower than the gate force	**D5. Boat acceleration**	All forces are decreasing, but the foot-stretcher force is decreasing faster than the gate force, which produces the highest boat acceleration. The rower's and system's acceleration decrease. The oar crosses the perpendicular to the boat. The handle and trunk achieve their maximal speed.
6	The system's acceleration becomes negative. The centre of the blade crosses the water level	**D6. Blade removal**	The handle continues to move towards the bow. The arms achieve the maximal speed. The rower's mass is begins the recovery phase (negative acceleration). Nearly zero boat acceleration
7	Release, end of the drive. The oar handle movement changes direction toward	**R1. Arms and trunk return**	The moment of inertia transfers from upper rowers' body to the boat mass. This causes a quick positive peak of boat

	the stern		acceleration and negative rower's acceleration
8	The seat starts moving toward the stern. This causes an increase of the boat's acceleration and a quicker decrease of the rowers' center of mass acceleration	**R2. Legs return**	The boat acceleration is positive (depending on the stroke rate), but rower's and system accelerations are negative. The legs speed towards the stern increasing. Arms are nearly strait, trunk crosses the vertical position
9	Rower starts pushing foot-stretcher. The speed of the seat decreases and the boat's acceleration becomes negative	**R3. Catch preparation**	Rowers push the stretcher stronger. This causes the boat deceleration, but rowers' centre of mass starts acceleration. Arms and oars prepare for the blade entry to the water.

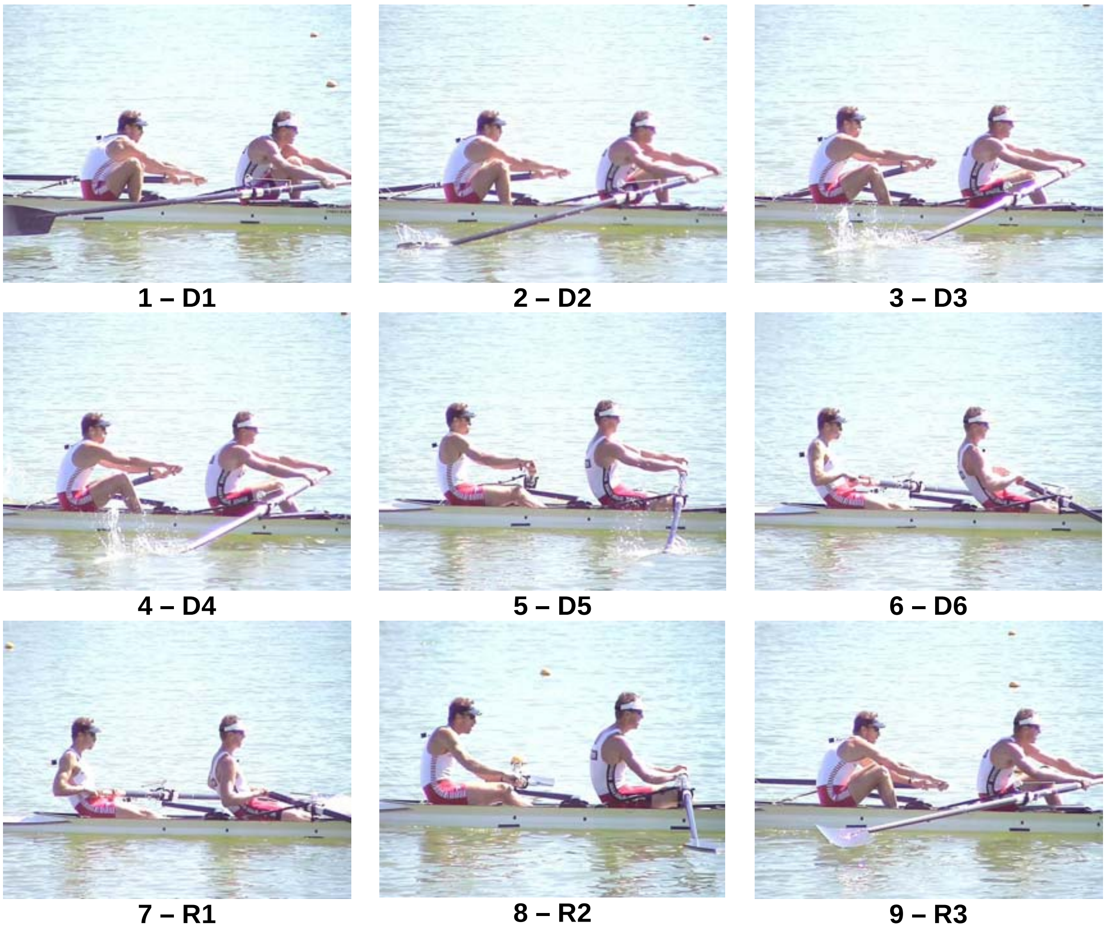


Figure 9. Micro-phases of the stroke cycle (key event and the following phase). Men's pair James Tomkins and Drew Ginn, Olympic Champions of Athens Games 2004. Stroke rate 36.5 str/min, video 25 fps, frame number – micro-phase.

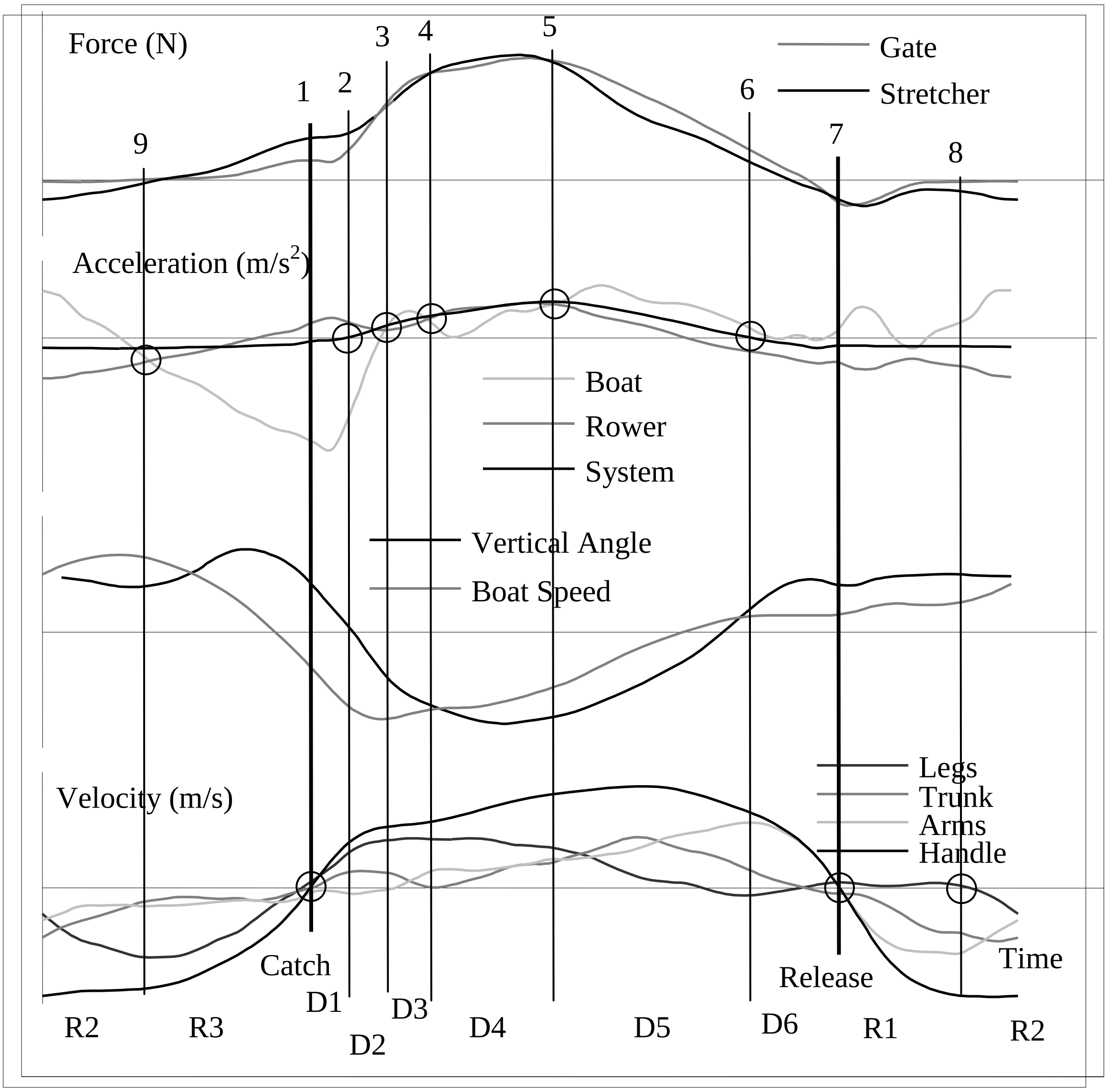


Figure 10. Biomechanical parameters and micro-phases of the stroke cycle (M1x, rate 32 str/min). Key events are marked with circles.

During D1 – D2 the rowers push to accelerate their body mass and decelerate the boat, because they have to change direction of their movement from the stern to bow at catch. The quicker these micro-phases, the better. Then, during D3 the rowers accelerate the boat to create faster moving support on the foot-stretcher to further accelerate their bodies. This micro-phase is extremely important for performing effective drive phase but in some crews this phase can be absent. Fast increasing of the handle force is the main condition of its presence.

During D4 the rowers push the stretcher again to accelerate themselves and accumulate the main part of kinetic energy. Effectiveness of this phase depends on the amount of gained boat speed during the previous D3 and fast powerful legs drive. The final boat acceleration micro-phases D5 and D6 utilize more pull by means of trunk and arms work. Forces and total system acceleration decrease during this phase and rower's acceleration become negative transferring kinetic energy to the boat. This push-pull-push-pull coordination during the drive requires coordination and "boat feel" from the rowers.

Biomechanical variables

Rowing provides an excellent model for biomechanical measurements. The first of such measurements were carried out by Atkinson in 1896. Since then, the biomechanical measurements have become common practice both for research and athlete training purposes in major rowing countries. The main variables of the rowing biomechanics are: the oar angle, force application, boat velocity and acceleration, and body segments movement.

Oar Angle

The horizontal oar angle defines the amplitude of the rower's movement. The angle is measured from the perpendicular position of the oar relative to the boat axis, which defines zero degree. The catch angle is defined as the minimal negative angle and the release angle is the maximal positive angle. The horizontal oar angle is used for definition of the start of the stroke cycle, which occurs at the moment of zero oar angle during recovery (Kleshnev, 2005).

Table 7. Average oar angles in different categories of rowers at racing stroke rate

Categories	Catch angle	Release Angle (deg)	Total Angle (deg)
Men scull	-66.5	43.8	110.4
Men light scull	-64.5	42.6	107.1
Men sweep	-56.8	34.3	91.2
Men light sweep	-54.3	33.6	87.9
Women scull	-62.2	43.0	105.2
Women light scull	-61.3	42.8	104.2
Women sweep	-53.5	33.4	86.9

The total rowing angle can be 4% longer at the lower stroke rate 20-24 str/min.
A vertical oar angle is useful for defining of the rower's oar handling skills. It reads zero degree when the centre of the blade is at the water level and negative downwards.

Forces

The forces in rowing are usually measured at the handle and at the gate (pin).
The handle force can be determined by means of measuring the bend of oar shaft. The point of the handle force application is not certain, especially in sweep rowing, where the rower can pull more with the inside or the outside arm. This can create a problem if the ambitions is to know the handle force itself, but it produces more reliable values of rowing power applied to the handle, because it is calculated using the moment of force (Kleshnev, 2000).
The gate force is measured using specially developed instrumented gates. This method produces more accurate and informative data on the force applied to the boat, but calculation of the power from the gate force is not accurate.

Table 8. The handle forces and rowing power at racing rate in different categories of rowers

Rower's categories	Maximal Handle Force (N)	Average force during the drive (N)	Rowing power (W)
Men scull	766	405	528
Men light scull	692	360	464
Men sweep	671	331	520
Men light sweep	590	294	425
Women scull	547	286	329
Women light scull	477	253	285
Women sweep	479	238	308

The graph of the force relative to time or horizontal oar angle called "force curve", which is a valid indicator of rowing technique. Peak force develops earlier in big fast boats and at higher stroke rate.

Body segments input

On average, each of three body segments contributes approximately one third to the total length of the stroke arc (legs a bit more, trunk a bit less). The legs execute their work during the first half of the drive, when the force exertion is maximal. Therefore, the legs produce nearly half of the rowing power (46%); the trunk produces nearly one third (32%) and arms a bit more than one fifth (22%). As higher stroke rates the legs increase their percentage contribution power. Thus, trunk muscles utilize only about 55% of their work capacity during rowing. At the same time, the arms use about 75% and the legs up to 95% of their respective work capacity.

Rowing technique

Rowing styles and efficiency

Rowing styles are defined by movement of two biggest body segments: the legs and the trunk. The most popular attempt of classification of rowing styles was by Klavora (1977), which defines the following three main styles.

- The **Rosenberg** style is named after Allen Rosenberg, who was the head coach of many USA national rowing teams from 1961 to 1976. This is the most traditional style and inherits developments in technique introduced by the great English-Australian coach Steve Fairbairn in the end of 19^{th} - early decades of the 20^{th} century. This style is characterised by large forward declination of the trunk at the beginning of the stroke, then strong leg extension without significant trunk activation. At the end of the cycle the trunk stops in the deep backward position.
- The **Adam** style was developed in 1960-s by the innovative coach Carl Adam from West Germany. This style has a comparatively long leg drive, limited amplitude of the trunk and simultaneous activity of legs and trunk during the stroke.
- The **DDR** style was developed by coaches and scientists of East Germany – the most successful rowing nation in 1970-s. The style is characterised by large, forward declination of the trunk, which begins the drive, followed by simultaneous activity of the legs.

Two main factors, which distinguish these styles are timing (simultaneous or consequent activity of two biggest body segments) and emphasis during the drive (on legs or trunk). These factors can be illustrated as X and Y axes of a quadrant (Figure 11).

The three mentioned styles perfectly fit three quarters of the quadrant. However, a fourth rowing style exists. This style has consequent timing and emphasis on the legs drive. This style may be called the “**Grinko** style” after the talented Russian coach Igor Grinko who coached World Champions M4x of USSR and then 1990 World champion and 2004 Silver Olympic medalist in M1x Jueri Jaanson. This style inherits the traditions of the USSR school of rowing technique, which produced great rowers in 1950-60 including three times Olympic champion Viacheslev Ivanov.

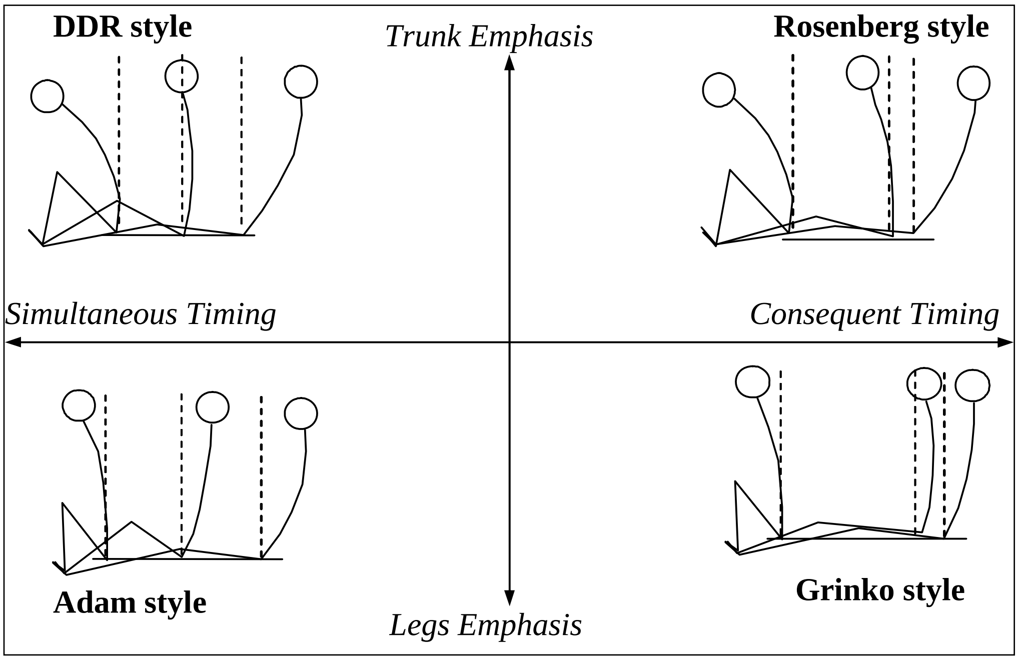


Figure 11. Quadrant of rowing styles.

The rowing style correlates with the shape of force curve, which affects amount of power generated and blade propulsive efficiency. A sequenced work of the legs and trunk (Rosenberg and Grinko rowing styles) usually produces triangular shape of the force curve and higher peak force and power values (Figure 12). This leads to higher slippage of the blade through the water that causes energy losses. Lower blade propulsive efficiency, however, can be more than compensated for by higher values of force and power produced per kg of body weight. Active use of the trunk produces even more power and the Rosenberg style can be considered as the most powerful rowing style. Simultaneous work of the legs and trunk (the two German rowing styles) produces more rectangular shape of the force curve, but the peak force and power are lower (Figure 12, b). More even pressure on the blade improves its propulsive efficiency. However, slower and more static character of the legs and trunk work does not allow delivering its optimal power.

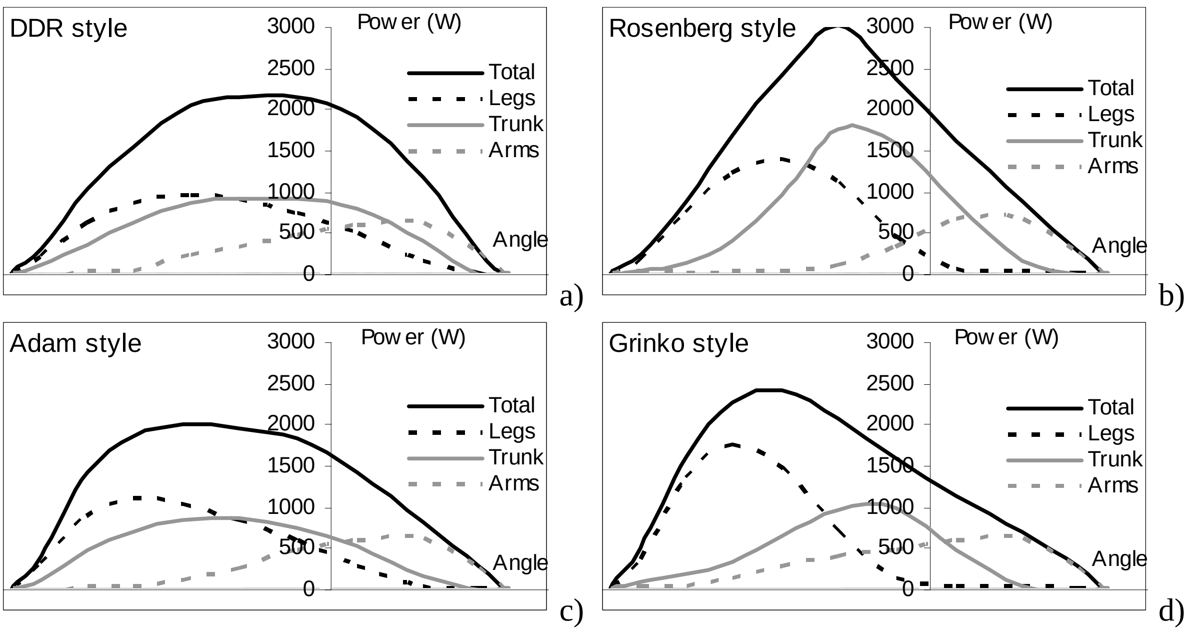


Figure 12. Effect of the segments sequence and emphasis on the shape of power curve.

Emphasis of legs or trunks work affects position of the peak force and power. Styles with the legs emphasis (Adam and Grinko styles) allow quicker increase of the force and earlier peak of the force curve. This increases the initial boat acceleration micro-phase D3, improves the temporal structure of the drive and makes it more effective.
Styles with the trunk emphasis (Rosenberg and DDR styles) produce more power because of better use of big muscle groups as the gluteus and longissimus muscles. However, these muscles are congenitally slow because they are intended to maintain body posture. This fact together with the significant mass of the torso do not allow for a quick increase of the force and shift the peak of the force curve closer to the middle of the drive, making the temporal structure of the drive less effective.

It is, however, uncommon that these rowing styles are found in their pure form. Most rowers adopt a hybrid style in-between these four extremes. The choice of style depends on many factors including body structure of the rowers. For example, it is unlikely that rowers with short legs will adopt a style that emphasises the importance of a long slide.

Coordination, coaching and feedback

Rowing looks quite simple, but in fact it requires very high coordination and sophisticated motor control. The rower has to coordinate his body movement along with the oar's 3D movement and to maintain the balance of the boat. The task becomes even more complicated in crews, where each rower has to synchronise his movements with that of other members of the crew.
Due to short time of the drive phase (<1 s) and the fast movement of big muscle groups, rowers can not change movement pattern during the drive. They can only evaluate their sensations after completion of each stroke and make corrections for the next one.
The coach watches the crew and compares his visual impression with the an ideal model of the rowing technique. He then gives verbal feedback to the rowers, which can have more or less immediate nature: after each stroke, after completion of a bout of training, after a session, a day, or a week. A good coach also asks for feedback from the athletes that help him to evaluate the effectiveness of his actions and to find better methods of technique correction.
Several technical tools have become popular for giving feedback to rowers and coaches:

- StrokeCoach and SpeedCoach ™ provide immediate feedback on stroke rate and boat speed;
- Visual feedback can include videotape and replay after the session or in immediate mode using a personal head mounted display;
- Biomechanical data acquisition systems can measure the force applied by the rower, oar angles and other mechanical parameters (seat and trunk position, etc.).

This equipment looks attractive and are powerful tools for correction of rowing technique. However, it is necessary to understand what needs to be corrected and in what direction. Proper theory of rowing biomechanics is crucial when using technical methods of rowing technique correction.

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