THE PHYSICS OF ROWING
Force and moment

- Force is every influence which causes a body to move, change direction or deform.
  \[ F = m \times \vec{a} \]
  - The unit of force is 1 Newton.
    - \( N = \text{kg} \times \text{m} \times \text{s}^{-2} \)

- Moment is the action of force at a distance from an axis tending to rotate or deform a body.
  - The unit of moment is 1 Joule.
    - \( J = N \times m = \text{kg} \times \text{m}^2 \times \text{s}^{-2} \)
  - Do not confuse moment with momentum.
Work and power

- Work is the action of force on distance.
  \[ W = F \times s \]
  - The unit of work is 1 Joule.
    - \( J = N \times m = kg \times m^2 / s^2 \)

- Power is work performed over a certain amount of time.
  \[ P = \frac{W}{t} \]
  - The unit of power is 1 Watt.
    - \( W = N \times m \times s^{-1} = kg \times m^2 \times s^{-3} \)
1. Propulsion

body mass + force = movement
1. Propulsion

For example, if the mass of boat and crew $m_b = 100$ kg (single) accelerates to $v_b = 1$ m/s, $m_v = 10$ kg of water must be accelerated to $v_b = 10$ m/s, or $m_v = 20$ kg of water to $v_b = 5$ m/s.

Any combination of $m_r$ and $v_r$ yielding $m_v v_v = m_b v_b = 100$ kg m/s is possible.
1. Propulsion

- During stroke (when the boat is already moving) the backward movement of water pushing the boat forward is less noticeable. Oars seem to have „caught” the water. A look at the eddy created by the oar leaving the water shows that the water moved.

- For a boat to accelerate, the oars must fall through, but to the minimum extent possible.
1. Propulsion

Diagram of the position of the blade and forces acting on the blade

Source: Valery Kleshnev, PROPULSIVE EFFICIENCY OF ROWING, Australian Institute of Sport, Canberra, Australia
1. Propulsion

- During grasp and at the end of the stroke the propulsive efficiency of oar blade is higher due to hydro lift.
  - Propulsive efficiency of rowing, Valery Kleshnev, Australian Institute of Sport.

- In the middle of the stroke, propulsion is mostly due to the action of forces on oar blade.

- The precise share of the hydro lift has not been measured yet.
1. Propulsion

- Prevailing hydro lift
1. Propulsion

- The beginning of the prevailing action of force on the blade pushing the water
1. Propulsion

- The reappearance of hydro lift
1. Propulsion

- Overly long stroke is inefficient:
  - hands are too weak and unable to maintain the thrust of legs and trunk and
  - there is no hydro lift.
1. Propulsion – increasing the thrust

- by choosing larger-surfaced blade,
- by harder transmission,
- by using the “hydro lift” effect by applying more force at the beginning of the stroke with a sharp oar angle,
- by keeping the oar blade at optimum depth under water at a 4 - 6 degree angle.
2. Drag

- Bodies moving through fluids slowly decelerate due to **drag**. Drag is the transfer of an impulse of force from body to fluid.
- There are several types of drag during boat movement:
  - **Skin Drag**, due to the friction between water and part of the boat under its surface (~ 80%);
  - **Form Drag**, due to the turbulence created by the movement of the boat through water;
  - **Wave Drag**, due to the energy lost on making waves.
2. Water drag

- Skin drag is proportionate to squared speed. If skin drag is assumed to prevail, total drag \( R \) can be described as:

\[
R = a \cdot v^2, \quad (2.1)
\]

- That means that if you wish to double boat speed you need to put in \( 2^3 = 8 \) times more power.

- Or, if the power doubles, the speed increases by only \( 1.26 \) (=\( 2^{1/3} \)) times.

Consequently, when rowing with full power, crew rowing with half power is more difficult to overtake than expected.

The condition of submerged boat surface is more important for speed than boat mass.

For those who wish to learn more: http://www.sciencebits.com/rowers
2. Air drag

The air has similar influence (air is a fluid as well). The effect of the drag of still air is only several percentages of water drag.

- The speed of air is more subject to change, i.e. the influence of air at high bow wind can be tens of percents of total drag.

- The influence of form is relevant for air drag (bodies of the rowers, oars, boat with riggers).

- Oar rotation is relevant:
  - Oar speed is approx. 15 m/s or 50 km/h, and drag increases with the square of speed (Filter K.B. 2009)
3. Kinetic energy

- **Total kinetic energy** $E_k (= \frac{1}{2} \times \text{mass} \times \text{speed}^2)$ remaining in the system after stroke:

$$E_k = \frac{1}{2} m \dot{c} \dot{v}^2 + \frac{1}{2} m \dot{v}^2, (3.1)$$
3. Kinetic energy

- In this case, the two preceding examples have different results.

If \( m_v = 10 \text{ kg} \) and \( v_v = 10 \text{ m/s} \),
\[
E_k = 0.5 \times 100 \times 1^2 + 0.5 \times 10 \times 10^2 = 50 + 500 = \textbf{550 J}, \quad (3.2)
\]

But if \( m_v = 20 \text{ kg} \) and \( v_v = 5 \text{ m/s} \),
\[
E_k = 0.5 \times 100 \times 1^2 + 0.5 \times 20 \times 5^2 = 50 + 250 = \textbf{300 J}, \quad (3.3)
\]

- That is the basic reason behind selecting oar blade size in keeping with the principle „larger is better“, and keeping oar depth until the end of the stroke.

- That is one of the reasons why, if equipped with the same number of rowers, sculling boat is faster than sweep boat (total blade surface is larger).
4. Center of mass

- Rowing boat is not a single solid body – it consists of three separate parts:
  - crew, 70-80% of total mass;
  - boat (with cox), 20-30% of total mass;
  - oars, under 5% of total mass, to be ignored for now.

- **Center of mass** (CM) of the entire system is the average of the centers of mass of its parts.

- The system’s center of mass cannot change its quantity of motion (nor speed) without the action of an external force (again Newton’s First Law).
4. Center of mass

- **Example 4X:**
  - Total mass of rowers: 375 kg, (85.4%)
  - Boat mass: 52 kg, (11.8%)
  - Oar mass: $8 \times 1.4$ kg = 12 kg, (2.8%)
  - Total: 439 kg
4. Center of mass

When crew moves towards the stern at speed $-v_p$ relative to speed $v_t$, to maintain the quantity of movement, the boat must move forward at the second relative boat speed $v_c$:

$$m_s \, v_t + m_b v_t = m_c (v_t - v_c) + m_b (v_t + v_b), (4.1)$$

or

$$m_c \, v_c = m_b v_b, (4.2)$$

*RBN 2010/06 – uniform speed of the rowers’s CM contributes more than uniform boat speed.*
4. Center of mass and kinetic energy

1. Stroke must be pronounced, as strong as possible, because it is only during the stroke that the speed of system is increased;

2. during the stroke focus must be on the acceleration of the rowers’ mass, since it is the greatest accumulator of kinetic energy;

3. the total quantity of energy accumulated during stroke defines average system speed;

4. force on footboard must be pronounced, since it is the only force accelerating the rowers’ center of mass;

5. during carry over for the next stroke the kinetic energy of the rowers’ CM is transferred to the boat’s CM, accelerating it.
4. Influence of additional mass

- Additional mass has three components influencing speed:
  - greater drag due to increased mass and larger quantity of displaced water (larger submerged surface, increased form drag, larger wave) (-0.061%);
  - higher loss of inertia during the movement of the centers of mass moved by a rower (-0.240%);
  - small energy loss due to minor changes in boat speed (higher inertia – larger quantity of movement) (+0.110%).
- Total change of speed due to an increase in system mass by 1 kg is -0.191% (RBN February 2009)
  - Larger (unnecessary) rowers’ mass is more harmful, due to the larger influence of loss of inertia, than larger boat mass, due to the positive influence of minor changes in boat speed.