Determining the effectiveness of oar blades in rowing

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Abstract
Objective of the study is to identify the main theoretical principles and measurement methods and provide practical examples of how to correctly determine the efficiency of a rowing blade in academic rowing.
Methods and structure of the study. A telemetric system was used for measurement, which allows for accurate measurement of effort, oar angles and boat movement, and uses this data to reconstruct the trajectory of the oar in the water during the stroke.
Results and conclusions. On average, the hydro-lift force provides about 56% of the total force on the blade, and the drag force provides the remaining 44%. The total drift of the blade center along its curved trajectory is 1.7 m, and the total blade efficiency is 80.5%. The oar blade is a fairly efficient propulsion device compared to the 24% average physiological efficiency of a rower. Therefore, of all the metabolic energy consumed by the athlete, less than 6% is lost to blade drift, and most of it is dissipated as heat in the rower's body. The blade's efficiency was higher at the beginning and end of the stroke, so it is advantageous to quickly increase the effort after the catch and maintain it longer at the end, in other words, to make the effort curve more rectangular. This is also useful for both overall power and the effective dynamics of the rowing system.

Keywords: *academic rowing, mechanical efficiency, oar blade, measurements.*

Introduction. The propulsive efficiency or efficiency of the oar blade is a popular topic of discussion in the rowing community, and opinions remain quite controversial. The traditional view, as outlined in rowing textbooks [1, 2, 3] is that when the oar is at an acute angle at the beginning of the stroke, a force perpendicular to the boat's velocity vector arises, which 'compresses the oarlock inward rather than propelling the boat,' resulting in a loss of rowing power and making the oar less effective. This controversial position is easily refuted [4] if we return to the basics of mechanics, according to which power is the scalar product of the force and velocity vectors (their magnitudes multiplied by the cosine of the angle between them), so when these vectors are mutually perpendicular (cosine 90˚ = 0), the power is zero. Since the lateral force is perpendicular to the speed of the boat, it does not create energy losses and does not reduce the efficiency of the oar blade, but only changes the ratio of force and speed of the rower's work, i.e., makes the dynamic transmission of the oar heavier. A similar dynamic transmission effect can be found in many other modes of locomotion, allowing higher speeds to be achieved with lower propulsion speeds:

- When a speed skater or skier uses the skating technique, the force of the push is directed sideways, but the athlete moves forward faster than a runner who pushes the support straight back.
- Sailing yachts travel faster in side winds and even headwinds than in tailwinds, etc.

There are many publications in foreign literature on the mechanics and efficiency of oar blade operation [5, 6, 7], but this topic has not yet been sufficiently covered for domestic rowing specialists.

Objective of the study is to identify the main theoretical principles and measurement methods and provide practical examples of how to correctly determine the efficiency of a rowing blade in academic rowing.

Methods and structure of the study. Similar to other modes of locomotion, the efficiency of the oar blade is part of the total mechanical energy produced by the athlete, which is directed towards propelling the athlete-equipment system. When a rower applies force to the oar blade, it 'slips' through the water, i.e., there is a displacement of the fulcrum and a loss of power *Pw*, which can be defined as the scalar product of the force vector *F* and the velocity vector *Vbl* at that point by the cosine of the angle between them.

$$Pw = F\ Vsl\ cos(\varphi) \quad (1)$$

These losses are deducted from the total power, and the remainder is the propulsive power that drives the entire system forward. The general definition of efficiency is the ratio of propulsive power to total power:

$$E_{bl} = P_{prop} / P = (P - P_w) / P \quad (2)$$

To measure these values, the BioRow telemetry system was used, which allows for accurate measurement of effort, oar angles and boat movement, and uses this data to reconstruct the trajectory of the oar in the water during the stroke.

Results of the study and discussion. When analyzing the blade movement in detail (during the working phase of the stroke cycle), the system allows you to determine the velocity vector *Vbl* at the center point of the blade, the angle of attack relative to the water *Aa* (it is important to take into account the bend of the oar), and the force applied to the center of the blade *Fbl*, which can be obtained from the force on the handle and the gear ratio. In this case, the center of the blade moves forward with the boat from the catch to an angle of approximately -25˚ before the perpendicular, and again after an angle of 15˚ after the perpendicular and until the end of the stroke, so that the blade moves backward only 35% of the stroke time and floats backward only about 12 cm. The outer edge of the blade floats back more (about 30 cm), but the inner edge of the blade does not float back at all and always moves forward with the boat. During the entire stroke, the center of the blade moves 1.68 m forward with the boat.

If the blade moves through the water at an angle of attack *Aa* different from 90˚, then a lifting force *Flift* (hydro-lift) arises and the blade acts as an underwater wing. The hydro-lift force *Flift* is always directed perpendicular to the velocity *Vbl.w* and has 100% efficiency. All energy losses depend on the drag force *Fdrag*, which always has a direction opposite to the blade speed *Vbl.w*. *Flift* and *Fdrag* are components of the total reaction force *Freact*, which has the same magnitude and is directed opposite to the force on the blade *Fbl*. *Freact* is transferred through the oar shaft and broken down into the aforementioned *Fprop* and lateral force *Fside*, which does not cause energy loss as it is perpendicular to the boat's speed. It is important to note that any slippage of the blade in the water causes energy loss, regardless of direction, even if the blade is moving forward with the boat.

On average, the hydro-lift force provides about 56% of the total force on the blade, and the drag force provides the remaining 44%. The total drift of the blade centre along its curved trajectory is 1.7 m, and the total blade efficiency is 80.5%.

The equation determining the blade efficiency is quite complex and includes the blade drift speed *Vbl*, the force at its center *Fbl*, and the angle of attack *Aa* as well as the water density *ρ*, the blade area *S*, and the total drag coefficient *k* (which depends on the blade shape and angle of attack):

$$Ebl = 1 - sin(Aa) / (k\ \rho\ S)^{0.5}\ Fbl^{0.5} / Vbl \quad (3)$$

This equation can be useful for determining the factors that affect the efficiency of a paddle blade:

The efficiency of the blade is higher at a steeper angle of attack *Aa* (*sin(Aa)* becomes smaller), which occurs at the beginning and end of the stroke.

The blade efficiency is higher when any of the factors *k ρ A* increases: the blade shape is more efficient (*k*↑), and/or the water density is higher (*ρ*↑), and/or the blade area is larger (*A*↑).

The blade efficiency is higher when the force on the blade *Fbl* is lower, which occurs at the beginning and end of the stroke, and (together with a sharper angle of attack) explains the increase in the efficiency curve. With the same force on the handle, the force on the blade is lower when the outer lever of the oar is shortened and/or the inner lever is lengthened, so the blade efficiency is higher with a heavier oar gear ratio. If the force on the blade approaches zero, its efficiency increases to 100%, but the blade does not create propulsion and becomes useless. For this reason, stronger rowers in a team usually have lower blade efficiency and vice versa (however, with some exceptions).

The efficiency of the blade increases at higher speeds *Vbl*, which depends on the speed of the boat. Therefore, the efficiency of the blade is higher in large, fast boats or in fast weather conditions (tailwind), even if the blade's slip remains constant and its performance in the water does not improve.

The last point above suggests that blade efficiency may not be a complete measure of the quality of the oar's performance, so we tried to find other indicators and developed the concept of the blade drag coefficient DF_{bl}, which is defined as the ratio of the force on the blade F_{bl} to the square of its slip velocity V_{bl} in the direction perpendicular to its axis ($DF_{bl} = F_{bl} / V_{bl}^2$). DF_{bl} does not depend on the speed of the boat, but becomes very high at the beginning and end of the stroke, when the blade's drift is small, which makes it difficult to analyze. It has been found that the average DF_{bl} is more than 100 times higher than the boat's drag coefficient (approximately 3 for a single scull), which is the reason why it is possible to propel the boat-rower system forward.

With an average efficiency of around 80%, the oar blade is a fairly effective propulsion device, compared to 24% for the average physiological efficiency of a rower. Therefore, of all the metabolic energy consumed by the athlete, less than 6% is lost in the blade's descent, and most of it is dissipated as heat in the rower's body.

Various factors have opposite effects on the efficiency of the blade and the rower, so it is important to find the optimal balance between them. For example, a heavier gear ratio and a larger blade area increase the efficiency of the oar, but slow down the speed of the handle, which leads to a longer stroke time, a decrease in rowing pace and power, and can reduce the rower's efficiency and rowing speed. Also, a large blade makes it harder to catch and finish the stroke and can create more aerodynamic drag on the preparation.

Other factors have a unidirectional effect on efficiency components: since blade efficiency is higher at the beginning and end of the stroke, it is beneficial to quickly increase effort after catch and maintain it longer at the end, in other words, to make the effort curve more rectangular. This is also beneficial for both overall power and the effective dynamics of the rowing system.

Conclusions. The efficiency of the blade and its drag coefficient can be used to assess the quality of the equipment and the skill of the rower, but for the best sporting results, other components must be taken into account and their optimal balance found.

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