SHORTER OARS ARE MORE EFFECTIVE

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ABSTRACT:

The purpose of this investigation was to clarify the effects of blade design and oar length on performance in rowing. Biomechanical models and equations of motion were developed to identify the main forces that affect rowing performance. Also, the mechanical connection between the propelling blade force and the force that the rower applies on the handle was established. On this basis it was found that the blade design and oar dimensions play a significant role on the rowing performance. While rowers have found empirically that larger and/or hydrodynamically more efficient blade shapes need to be rowed with shorter oars, this paper explains this tendency from a biomechanical point of view. Based on the presented evidence, it can be concluded that shorter oars will allow rowers to improve the propelling forces without increasing the handle forces. These findings explain tendencies that started with the introduction of new blade shapes in 1991. A 2 x 2 factorial ANOVA was used to test the significance of the oar shortenings that occurred with the introduction of larger blade surfaces while international record times improved during all those years. Consequently, the findings of this investigation encourage coaches to further experiment with shorter oars and oar manufacturers to continue their blade development that would lead to even shorter oars, with the goal of continuous rowing performance improvements.

INTRODUCTION

In 1959 the famous German rowing coach Karl Adam introduced a new blade shape to the rowing community. As a physics teacher, he believed that a shorter then the commonly used long and thin blade would be better. To maintain the blade area, he increased the width of the blade. His crews won several gold medals with the new blades at the European Championships that were held in that year in Mâcon, France. Based on this success, this blade shape became the international norm for the next 30 years and was called the Macon Blade.

The theory was that longer oars would allow the blade to travel longer in the water and so create larger blade forces. (Adam et al., 1977, 170) At the same time, training methods and boat technology improved tremendously. Specifically, year-round training, strength and interval training were introduced. Athletes became considerably stronger and as a result they could handle ever-increasing oar lengths. For example, the length of sculls increased from about 2.95m to 3.02m. (Nolte, 1977) Also, the introduction of new boat building methods and materials increased the stiffness while reducing the overall weight of the shells. The new boats were able to withstand higher loads with less deformation and therefore, allowed the rowers to apply larger forces that could be transformed into propulsion.

Since the blade shape and area did not change during this time, it seemed logical that only a longer oar could achieve a larger blade force, leading to an increase in boat velocity. (Adam et al, 1977, 170) This belief became standard coaching knowledge and remains today.

In 1991 the oar builder Concept2 introduced a new blade called the “Big Blade” that varied from the Macon Blade by having an asymmetric shape and a larger blade surface area. It was believed that the blade improved the handling of the oar and it should only be shortened to offset the larger blade area while otherwise the oar should be as long as possible. Initial empirical testing by the boat builder revealed that the sculls produced the best performance when the oar length was shortened to 2.88m – 2.91m. (Concept2, 2008) However, coaches accepted the recommendations but remained reluctant to experiment with even shorter oars, since it was still believed that a certain oar length was necessary to reach high boat speeds.

While most of the oar builders followed with similar blade shapes and almost identical blade areas, in 2004, based on further practical testing, Concept2 introduced their so-called “Fat Blade” by again increasing the blade area. Once more, the overall length of sculling oars needed to be reduced to about 2.80m - 2.83m. (Concept2, 2007b)

<u>Figure 1 near here</u>

Nolte (2005, 131) was the first to present the idea that more skilled crews actually should use shorter oars than lesser skilled crews. However, the theoretical evidence for such measures was not presented. Although practical tests revealed that oar lengths needed to be reduced with the larger blade areas, the biomechanical connections between outboard lengths, blade shape/size and boat speed were not understood. Coaches were still inclined to use the longest oar possible, since the general belief persists that boat speed and length of the oar are positively related (Nolte, 2006).

Therefore, the purpose of the present paper is to investigate whether shorter oars may have a positive effect on boat speed.

THEORETICAL MODEL

In this section, the underlying biomechanical models for the total system, rower-shell-oars and the sub-system ‘oar’ will be presented for use in further discussion.

Concurring with Baudouin & Hawkins (2004) there are generally only two horizontal forces acting on the total system (rower-shell-oars): the propelling blade force F_{Bx} acting on blades of both sides of the shell and the resisting drag force F_D.

Figure 2 near here

The equations of motion for the x- and y-direction for this system are:

$$(1) \qquad \sum F_x = F_{B1x} + F_{B2x} - F_D = m * a_x$$

$$(2) \qquad \sum F_y = F_{B2y} - F_{B1y} = m * a_y$$

We assume that the rowers move the handles on both sides of the boat evenly, and apply forces symmetrically on each handle so that all lateral forces in the y-direction on the blades cancel each other out and the shell moves straight ahead in the x-direction.

$$(3) \qquad F_{B1x} = F_{B2x}$$

$$(4) \qquad \left|F_{B1y}\right| = \left|F_{B2y}\right|$$

This leads to:

$$\text{If: } (5) \quad F_{B1x} + F_{B2x} = F_{Bx}$$

$$(1a) \qquad F_{Bx} - F_D = m * a_x$$

$$(2a) \qquad 0 = a_y$$

This means that only the components in the x-direction of the blade forces can propel the total system and are therefore directly responsible for the speed with which the total system travels.

According to the impulse-momentum theorem, the actual increase in speed of the total system Δv is dependent on the size of the x-component of the blade force F_B, the drag on the shell F_D, and the length of time Δt that those forces act on the system:

$$(6) \qquad I = M$$

$$(6a) \qquad (F_{Bx} - F_D) * \Delta t = m * \Delta v$$

$$(6b) \qquad F_{Bx} * \Delta t - F_D * \Delta t = m * \Delta v$$

It must be pointed out that the combined system of the rower, the shell and the oars is a mechanical “system of linked masses which move relative to one another and relative to their common center of gravity. In addition to these movements relative to one another, the whole system moves forward. The mass of the boat is approximately 15% of the mass of the rower and therefore the boat moves significantly” in relation to the total system. (Affeld et al., 1993, S39) The forces on the total system act on it and influence its velocity v while the velocity of the shell v_S on the other hand follows a distinctively different pattern mainly due to the movement of the rower relative to the total system. (See fig. 3) According to equation (7), the resisting force on the shell is dependent on its velocity with c combining all constants including the density of the water, the cross-sectional area of the shell in the water and the drag coefficient influenced by the shape of the scull:

$$(7) \qquad F_D \approx c * v_S^2$$

It is assumed that the rower's pattern of motion relative to the boat would be consistent for whichever oar is used, so that the influence of the movement of the rower's centre of gravity on the drag force F_D would be constant in all cases studied in this research.

The total system, as well as, the shell move the same distance during one complete stroke cycle, so that their average velocities $\bar{v}$ and $\bar{v}_s$ per stroke are the same. However, while the course of total system velocity over one stroke is a direct reaction of the propelling blade force F_{Bx}, the course of the shell velocity v_S follows a distinctly different pattern.

<u>Figure 3 near here</u>

The force on the blade is generated by the rower's movement of the handle relative to the shell by exerting force on the oar handle. The rower 'pulls' on the handle and causes a torque relative to the oarlock O that turns the oar around this point on the shell (the axle of the oarlock) while the resulting movement of the blade in the water creates the propelling force that acts on the total system. (see Figure 4)

In general, the forces F_H, F_O and F_B are not always perpendicular to the oar shaft. However, for the subsequent discussion it will be assumed that these forces always act at a 90 degree angle to the oar shaft. This supposition in fact does not affect the general nature of the following arguments nor the final conclusions.

The forces on the oar are dependent on the geometry of the oar, particularly on the lengths of its levers L_1 (lever inside of the shell on which the rower applies the handle force) and L_2 (lever outside of the shell on which the blade force acts), and the blade design.

<u>Figure 4 near here</u>

The equation of motion for the moment of force around the oarlock O proves to be:

$$(8)\qquad \sum M_O = F_H * L_1 - F_B * L_2 - I * \alpha = 0$$

At this point it will be assumed that the product $I * \alpha$ is relatively small compared to the other parts of the equation and can be neglected for the purpose of the following discussion. Indeed, boat builders strive to keep the moment of inertia I small by using very light materials and moving the oar's centre of gravity close to the oarlock. Also, the oar's angular acceleration α is kept low by the rower, since abrupt movements are avoided. In addition, this factor has no bearing on the subsequent discussion. Thus, the above assumption seems reasonable. Therefore, it can be shown that the blade force F_B is directly proportional to the handle force F_H, since equation (8) can be transformed to:

$$(8a)\qquad F_H * L_1 = F_B * L_2$$

$$(8b)\qquad F_H = \frac{L_2}{L_1} * F_B$$

As a reaction to the blade's movement in the water, the blade force is created. The blade movement is such that significant lift and drag components exist on the blade. (Nolte, 1984; Young, 1991; Affeld et al., 1993; Pulman, 2004; Cabrera & Ruina, 2006; Caplan & Gardner, 2006) Therefore, the blade shape needs to be designed to efficiently create both components. For example, a large blade face is necessary to create drag, while the curvature of the blade increases the lift. (see Figure 5)

<u>Figure 5 near here</u>

The drag and lift components of the blade force follow the hydrodynamic laws:

$$(9) \qquad Drag: F_{B_D} = \tfrac{1}{2} * \rho * A * c_D * v_B^2$$

$$(10) \qquad Lift: F_{B_L} = \tfrac{1}{2} * \rho * A * c_L * v_B^2$$

ρ represents the density of the water, A the area that the blade presents to the upcoming flow of the water, c_D and c_L are the drag and lift coefficients and v_B the resultant velocity of the blade relative to the water. The blade area A is of course dependent on the size of the blade, while the coefficients are influenced by the shape of the blade and the angle of attack.

The goal of a rowing competition is to cover the race distance in the shortest time possible. Rowers seek to reach their goal by producing their maximum physiological power over the course of the race and applying it to the handle of the oar. At each moment of the race the rower produces a certain power P that would be considered the maximum power available at that stage of the race:

$$(11) \qquad P = F_H * \omega * L_1$$

This also means that the exerted force F_H is the maximum available handle force that the rower can apply at the oar angle velocity ω. Of course, the magnitude of both the handle force F_H and the oar angle velocity ω are closely related to each other and rowers control them to exert the appropriate amount of power according to their physiological ability and the point in the race. In addition, the oar angle velocity ω affects the time that is needed to cover the overall arc of the oar during a rowing stroke, which in return determines the cadence that the rower chooses at that part of the race. Without discussing this phenomenon here in more detail, it is expected that rowers would carefully control all of these variables to perform to the best of their ability. This means that the exerted handle force F_H represents the maximum force that a rower can produce at that particular point of the race.

Based on this and (8b) above it can be concluded that if rowers of a given performance level want to increase the blade force F_B without changing the inboard L_1, the outboard L_2 has to be shortened. Although the theoretical evidence is clear, such a change is of course limited in practice, since a shorter outboard with the same blade would consequently lead to a larger oar angle velocity ω and with this to a change in the kinematics of the rowing stroke. Therefore, rowers have to use hydrodynamically more efficient blades. This can be achieved with a larger blade area and/or an improved blade shape.

METHODS

Periodically, the international rowing association FISA (Fédération Internationale des Sociétés d'Aviron) conducts independent surveys of the equipment used at Olympic Games and World Championships carried out by members of the FISA Material Commission which consists of international experts in that field. The information of the equipment survey includes the dimensions of the oars that are used by National Team crews that participate in the championships except for the Gold medal winning German men's eight in 2006. Each National Team is allowed only to enter one crew per boat class in international championships and not all National Teams enter crews in all boat classes. This means that the data collected in the surveys represents the oar dimensions that are actually used by the best crews in the world in their most important competition of that year. One can assume that the experience of the expert coaches, the communication and exchange of information between the coaches together with some testing influenced the National Team crews to choose the oar dimensions.

For this paper the information for all FISA surveys since 1982 was used:

- ☐ 1982: World Rowing Championships Lucerne/Switzerland (Gelbert, 1982)
- ☐ 1988: World Rowing Championships Milan/Italy and Olympic Games Seoul/Korea (FISA Material Commission, 1988)
- ☐ 1999: World Rowing Championships St. Catharines/Canada (FISA Material Commission, 1999)
- ☐ 2006: World Rowing Championships Eton/Great Britain (FISA Material Commission, 2006)

In 1982 and 1988, every crew included in the survey used Macon blades, whereas in 1999, all crews used Big Blades. In 2006, all crews participating in the World Championships used Big Blades except one. The one exemption was the German gold medal winner in the men's eight who used Fat Blades. The measurements would have been very interesting, but could not be included in the survey, since the team did not allow the FISA commission to measure their equipment..

Fat Blades were introduced to rowing in 2005, but no official measurements of crews that use these blades in international championships are available so far. Therefore, the recommendations for the appropriate measurements of the new blade published by the manufacturer (Concept2, 2007b) are used to compare the levers for those oars.

RESULTS

Table 1 and 2 near here

Tables 1 and 2 show that the span and inboard dimensions used by the crews included in the surveys varied very little over the years, although different blade types were used. However, tables 1 and 2, and fig. 6 indicate a clear trend for a reduction in outboard length and an increase in blade area for the oars utilized in international high performance rowing.

Figure 6 near here

Data were analyzed using a 2 x 2 factorial ANOVA, in which oar type (Macon versus Big Blade) was used to predict rowing performance.

The main effect for oar type was statistically significant, F(1, 494) = 3074.92, $p< .001$. Inspection of the mean scores for these variables reveals that, overall, Macon Blades have significantly longer outboards than Big Blades. In addition, post-hoc analysis suggests that the difference between Macon Blades and Big Blades is greater in sculling than in sweep rowing which would need to be discussed further in a different study. The change in outboard length from the Macon Blades used in 1982 and 1988 to the Big Blades used in 1999 and 2006 is statistically very significant (F=3074.92, $p<.001$). The further change in outboard length of the Fat Blade oars represents another definite empirical argument for the above presented theoretical description of the effects that outboard has on rowing performance. The proposed length reduction for the Fat Blade clearly lies outside of the standard deviation of the outboard length for the Big Blade.

Over the analyzed time period, the performance in international rowing improved constantly. (Schwanitz, 1995; Schwanitz, 2000; Schwanitz, 2001; Nolte, 2005a)

Schwanitz (1995, 2000) calculated the reduction in race time for every Olympic cycle to be between 0.9% (men's eight) to 1.8% (men's single) of the total time rowed over the race distance.

DISCUSSION

It is the nature of competition that rowers try to maximize the velocity of the total system by generating their maximum physiological performance. Rowers apply maximum handle forces F_H to generate maximum blade forces F_B during the time of the drive. However, if rowers want to move faster, the blade force F_B must be increased. The presented arguments indicate that rowers have the chance to increase the blade force during the drive without applying a larger handle force and/or altering the movement pattern. A shorter outboard L_2 (formula (8b)) combined with a hydrodynamically more efficient and/or larger blade provide the opportunity for a larger blade force F_B (Formulae (9) and (10)). For example, if blade enhancements like the so-called "vortex-edge" or the blade shaping according to the "Delta Wing Effect" (Concept2, 2007) increase the lift coefficient c_L, the lift force F_{BL} in formula (10) enlarges. With this improvement, the blade force increases, so that the lever L_2 needs to be shortened to match the maximum handle force F_H.

In this case, the same hand force F_H could indeed produce a larger blade force F_B with a shorter outboard lever L_2 and it is hypothesized that this is exactly the reason for the decline of oar lengths with the blade developments that have occurred since 1991 (see figure 6).

The performance in international rowing increases constantly, which means that international rowers consistently improve race times. Many factors are responsible for this progress. The improvement in blade design and rigging is certainly one of these factors and the outlined development of the outboard length fits this argument.

In 1982 and 1988 only Macon Blades were used. The Big Blade compared to the Macon Blade has a better efficiency (Affeld et al., 1993), as well as, a larger blade area and is therefore capable of producing a larger blade force. Consequently, the outboard length L_2 was reduced in sculling by about 0.10m or 5%. The new blade offered the possibility of increased blade forces with the same handle force. While all international rowers used Macon Blades until 1991, it is understandable that this blade is no longer in use.

The Fat Blade that was introduced in 2005 represents the next development with a further enlarged surface area and provides according to Concept2 (2007) a higher efficiency. This means once more that the outboard length needs to be reduced and the first practical experiences indicate that outboard reductions of 0.09m or 5% can be expected.

Although the performance improvements stem from multiple influences, a higher boat velocity can only be reached by larger blade forces. The statistical analysis clearly demonstrates that shorter outboards are used to produce these larger blade forces.

Two questions can be asked with regards to the development of rowing blades and their usage:

1. Why are rowers reluctant to use more efficient and/or larger blades like the Fat Blade?
2. Why would one not use even larger blade areas?

From the above arguments it is clear that more efficient and/or larger rowing blades produce larger blade forces F_B that, if the outboard is shortened, a rower can apply to improve the speed of the total rowing system while generating the same handle force F_H. However, there are also challenges to overcome. Every change in equipment produces a change in feedback that the athlete receives while performing in their sport. For example, with a reduction of the outboard length, the weight of the oar may change, as well as the position of its centre of gravity. These modifications would affect the so-called balance point of the oar and together with an increase in stiffness through the reduction in length it would be expected that such a change would produce different feedback.

Furthermore, the vertical angle that the oar has with the water during the drive changes with an alteration in oar length, so that adjustments to the height of the oarlock relative to the water need to be made.

In addition, with the increased size of the oar it becomes more difficult to get the blade in and out of the water. Rowers would have to learn how to reduce the time to submerge the blade in the water (entry) and remove it from the water (release). According to Kleshnev (2002, 19), these times are strongly correlated to the success of a crew.

Therefore, rowers need to get accustomed to the new “feeling” of their equipment, especially during exhausting race conditions under the pressure of the competition and at high movement speeds. A rower can easily have some poorly executed rowing strokes because of the different feelings (e.g. the oar can hit the water or the balance is off) and these movement errors can result in loss of speed at least in some parts of the race. Consequently, rowers who are very happy with their training speed and the results achieved in racing using a conventional blade, may hold back changing the oars so as to avoid taking any risk of losing control.

Nevertheless, it can be predicted that more and more rowers will learn to handle the new blades and therefore, the blades of larger size and higher efficiency will replace the Big Blade over time.

Although there is a trend to use larger size blades, research needs to be done to see how large a blade and how short an oar can become while still optimizing performance. Theoretically, it was shown that a shorter outboard will allow a larger blade force, but rowers need to be able to handle such oars. While researchers and oar builders will be able to design larger blades, rowers and coaches need to practically validate their above mentioned benefits, while experimenting with shorter oars. Especially highly skilled athletes, who will handle the technical challenges of balancing the boat with shorter and lighter oars, as well as entering and releasing the blades in and out of the water, should be able to draw from the advantages that the new equipment offers.

The challenge is to design practical on-water tests that allow the comparison between different kinds of equipment. Also, strategies need to be developed to investigate associate equipment changes (e.g. spread, inboard, as well as footstretcher positioning in longitudinal direction) that could influence performance with the new blades.

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Figure captions

Figure 1

Comparison of the different blade shapes that developed over the years – Macon (a), Big Blade (b) and Fat Blade (c); all measurements in cm.

Figure 2

Free body diagram of the total system rower-shell-oars.

Figure 3

Velocities of the centers of gravity of the shell v_S (·········· ··), the rower v_R (▬ · · ▬) and the total system v (▬▬▬▬) over time for a world class single sculler. (After: Nolte, 1984, 222)

Figure 4

Free body diagram of the rowing blade with the geometry of the oar and the resulting movement ω around the oarlock O where the oar is connected to the rowing shell. (L_1 – moment arm of the handle force; L_2 – moment arm of the blade force)

Figure 5

Front, side and top view of a rowing blade to demonstrate features that are efficient for drag (e.g. front area, lip on top edge) and lift (e.g. thickness, curvature).

Figure 6

Development of outboard length and blade area over time. The data from 1982, 1988, 1999 and 2006 represents the measurements that were used by the participants of the World Championships or Olympic Games at that year conducted by the International Rowing Federation FISA. (Gelbert, 1982; FISA Material Commission, 1988; FISA Material Commission, 1999 and 2006). In 1982 and 1988 only Macon Blades were used. In 1999 only Big Blades were used. Although in 2006 one crew rowed Fat Blades (the World Champion German men’s eight), FISA did not include their measurements in the survey. Therefore, only Big Blades are represented in the data. FISA did not conduct measurements in 2007, so that for 2007 the recommended data from the oar builder was used. (Concept2, 2007)

a) Sculling blades

b) Sweep blades

Figures

Figure 1.

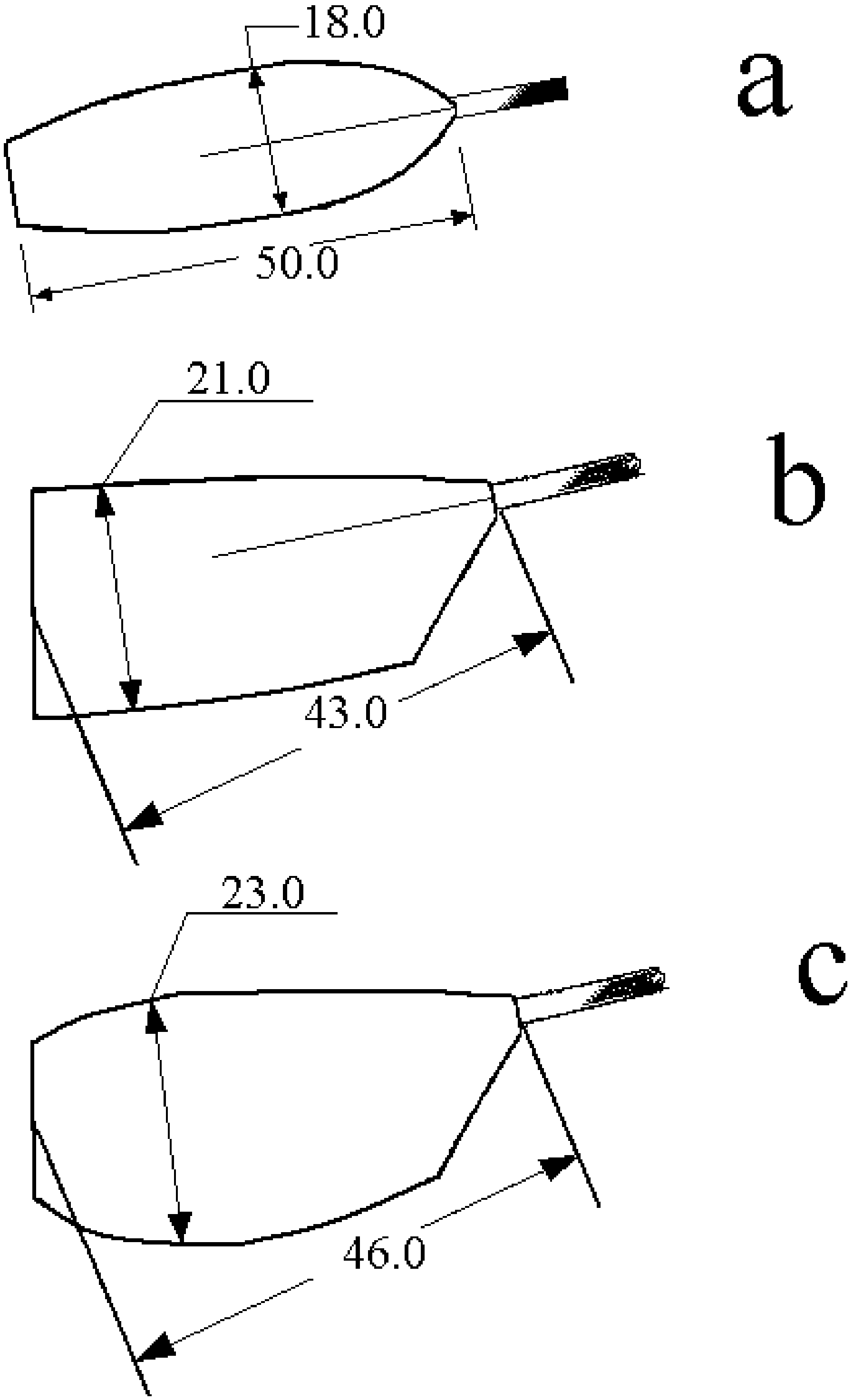
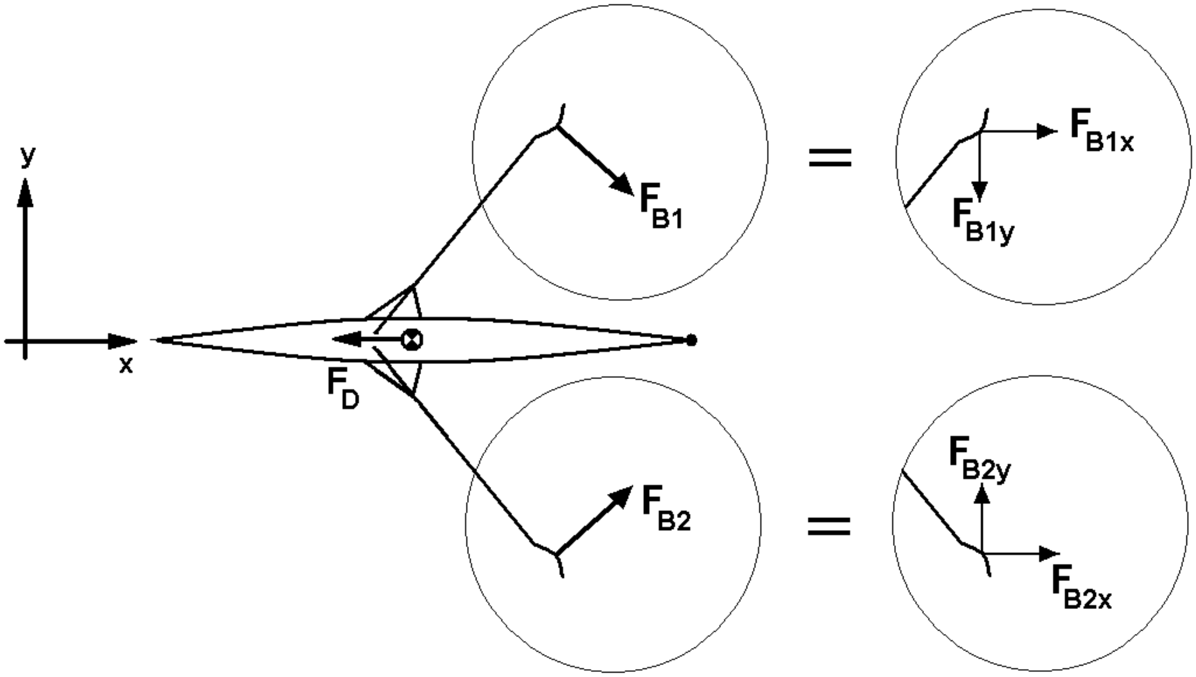


Figure 2.



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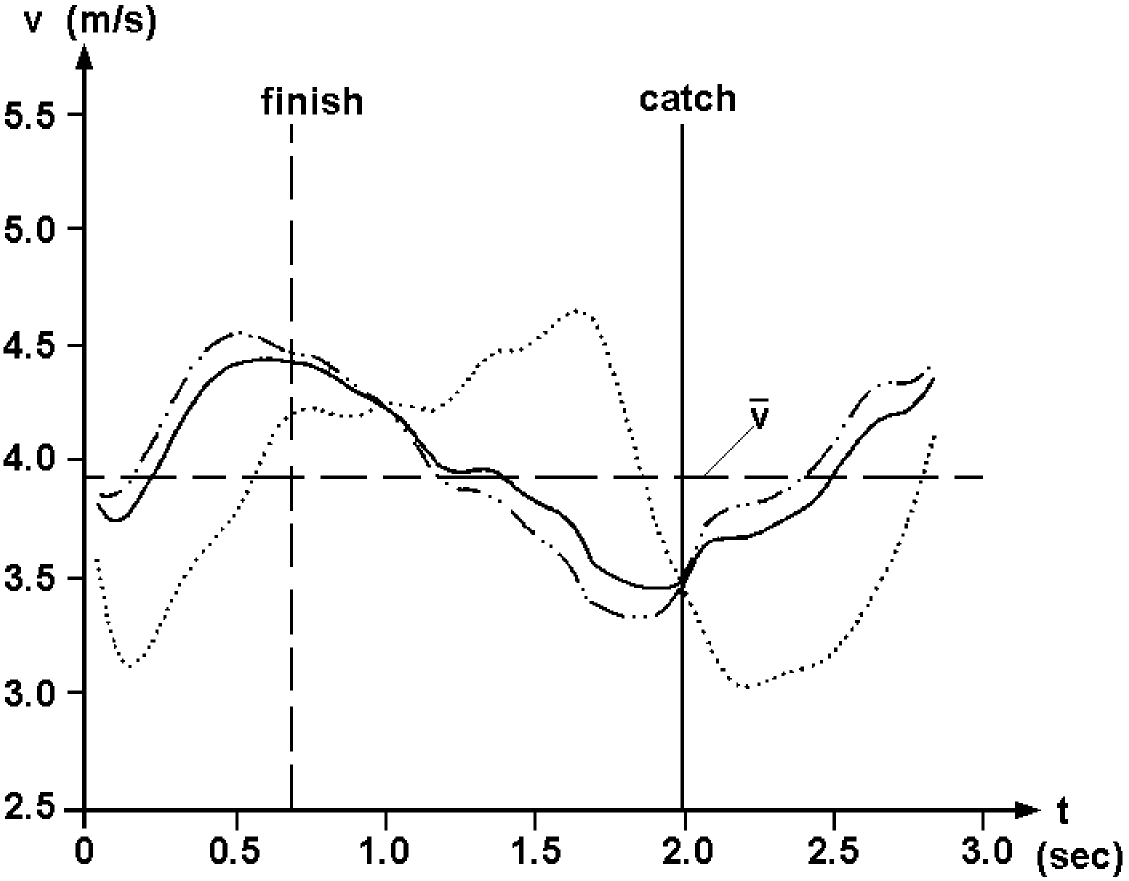

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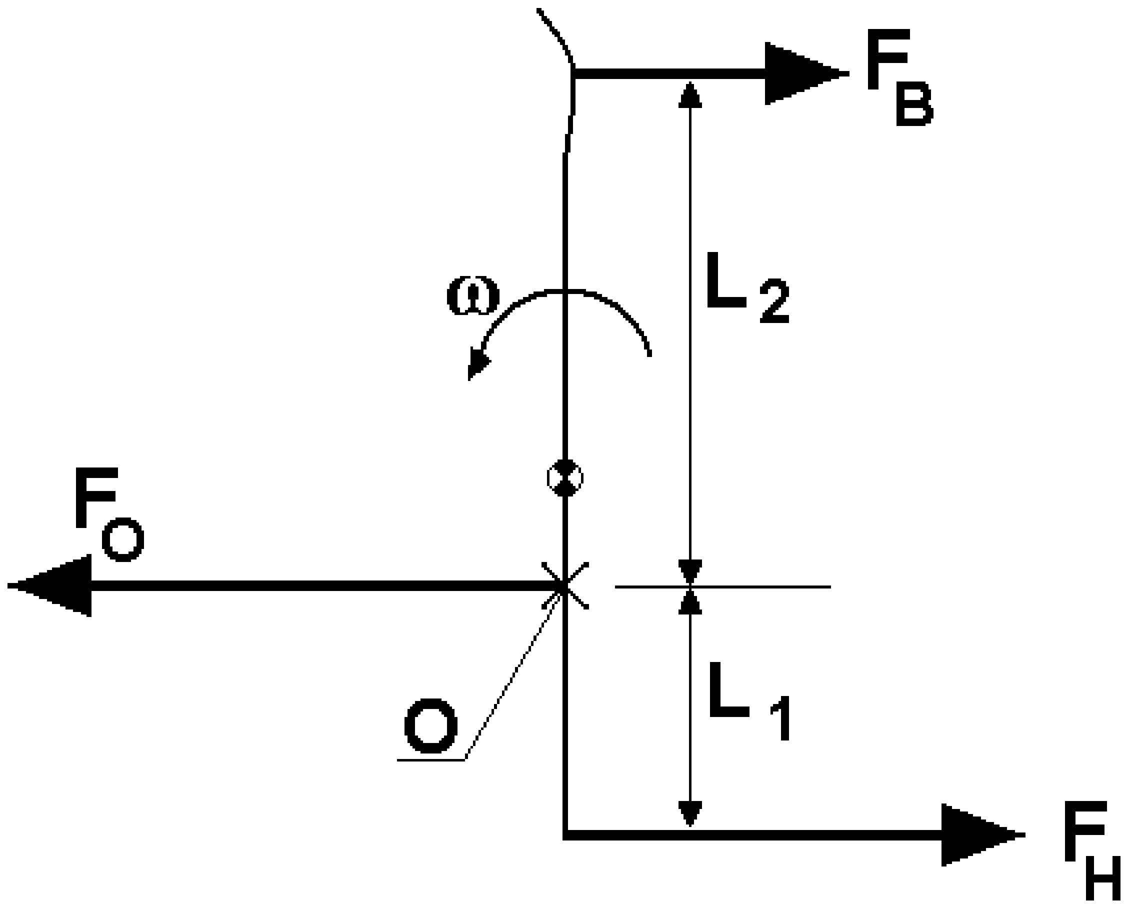


Figure 5.

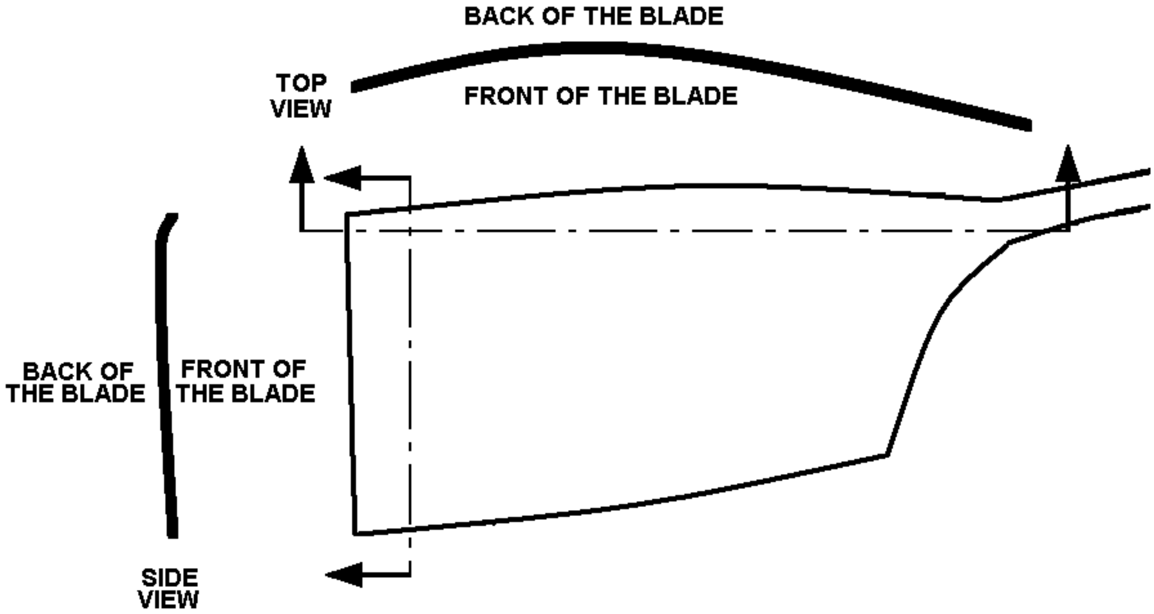
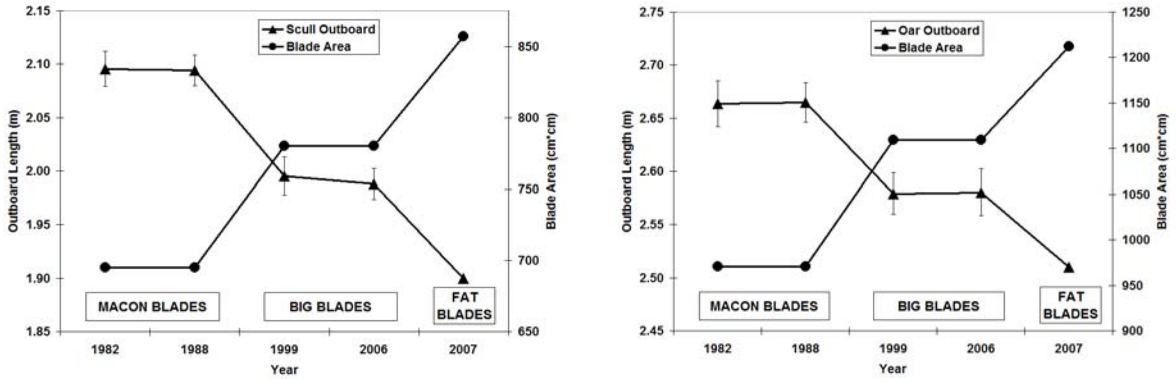

BACK OF THE BLADE
TOP VIEW
FRONT OF THE BLADE
BACK OF THE BLADE
FRONT OF THE BLADE
SIDE VIEW

Figure 6.



a) Sculling blades b) Sweep blades

Tables:

Table 1:

Mean and standard deviation of the inboard, outboard and span of all sculling boats officially measured at selected World Rowing Championships (WRC) and Olympic Games (OG), as well as data from Concept2 (2007a and 2007b).

Table 2:

Mean and standard deviation of the inboard, outboard and span of all sweep boats officially measured at selected World Rowing Championships (WRC) and Olympic Games (OG), as well as data from Concept2 (2007a and 2007b).

Table 1:

Year	Inboard		Outboard		Span		Blade	Blade	Source of data
	Mean	SD	Mean	SD	Mean	SD	Area	Type	
1982	0.87	0.01	2.10	0.02	1.59	0.03	695	Macon	WRC Lucerne/Switzerland
1988	0.88	0.01	2.09	0.01	1.59	0.01	695	Macon	WRC Italy / OG Korea
1999	0.88	0.01	2.00	0.02	1.59	0.01	780	Big Blade	WRC Canada
2006	0.88	0.01	1.99	0.01	1.59	0.01	780	Big Blade	WRC Great Britain
2007			1.90				857	Fat Blade	Concet2

Inboard, Outboard, Span in m; Blade Area in cm^2

Table 2:

Year	Inboard		Outboard		Span		Blade	Blade	Source of data
	Mean	SD	Mean	SD	Mean	SD	Area	Type	
1982	1.16	0.01	2.66	0.02	0.85	0.02	971	Macon	WRC Lucerne/Switzerland
1988	1.14	0.01	2.66	0.02	0.85	0.01	971	Macon	WRC Italy / OG Korea
1999	1.15	0.01	2.58	0.02	0.85	0.01	1109	Big Blade	WRC Canada
2006	1.15	0.01	2.58	0.02	0.85	0.01	1109	Big Blade	WRC Great Britain
2007	1.17		2.51				1212	Fat Blade	Concet2

Inboard, Outboard, Span in m; Blade Area in cm^2