SPORTSCIENCE sportsci.org

Perspectives / Performance

One Hundred and Fifty Years of Rowing Faster

Stephen Seiler

Sportscience 10, 12-45 (sportsci.org/2006/ssrowing.htm)

Agder University College, Faculty of Health and Sport, Kristiansand 4604, Norway. Email.

Reviewer: Allan Hahn, Australian Institute of Sport, Belconnen, ACT 2616, Australia.

Boat velocity has increased linearly by 2-3% per decade since the first Oxford-Cambridge boat race in 1829. Part of this increase is a result of recruitment of athletes from a population that has become taller and stronger. However, the increase in boat speed attributable to increased physical dimensions alone accounts for less than 10% of the total improvement, because the increase in rower mass has increased boat drag. A 10-fold increase in training load over the last 150 years probably accounts for about one-third of the increase in physical capacity and performance. The rest of the improvement is due to reductions in boat drag, increases in oar blade efficiency, and improvements in rowing technique. Boat design was revolutionized in the 19th century, the only substantial change since then being a gradual reduction in boat weight. Oar design and construction have evolved steadily, the most recent development being the introduction of cleaver or "big" blades in 1991. Improvements in rowing technique have increased boat speed by reducing boat yaw, pitch and roll, and by improving the pattern of force application. New tools for real-time measurement and feedback of boat kinematics and force patterns are opening new approaches to training of individual rowers and to selection of rowers for team boats. KEYWORDS: elite athlete, efficiency, history, performance, power, training.

Reprint pdf (2.1 MB) · Reprint doc · Slideshow (3.0 MB)

Rowing has been the focus of a great deal of research, with attention devoted mainly to potential limiters and enhancers of performance of well-trained rowers. Inspired by Alejandro Lucia's tutorial lecture on the science of the Tour de France at the 2005 ACSM meeting, I proposed and was accepted to present a tutorial lecture titled *150 years of scientific enquiry into rowing and rowers* for the 2006 meeting. In developing the lecture, I soon realized that there were too many isolated research topics and too many possible detours. So, I decided to focus on one central question: what can science tell us about the improvements in rowing performance over time and how they have happened?

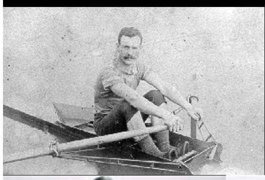
I have modified the presentation from the original lecture format, removing a video clip and adding some explanatory notes in green text on some of the slides. The PDF contains the slides in a printer-friendly format.

Reviewer's Comment

This wonderful presentation provides an excellent summary of factors influencing rowing performance. I certainly found it very instructive, even though I have been quite closely involved with rowing for more than two decades. The attempt to explain why rowing times have improved so dramatically over the past 150 years provides a clear theme that elegantly links the various items of information presented. Wherever possible, published references are cited, but the author has also shown a willingness to use current knowledge as a basis for informed surmise, and this adds an attractive dimension to the work. –Alan Hahn

Published September 2006

150 Years of Rowing Faster!



Stephen Seiler PhD FACSM
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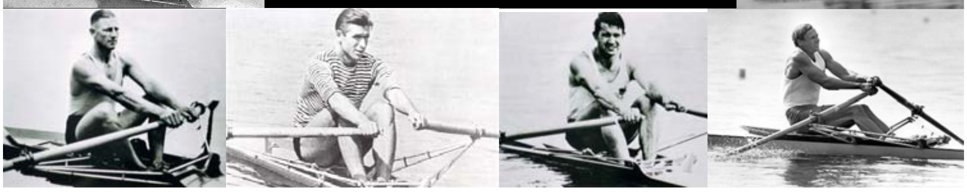
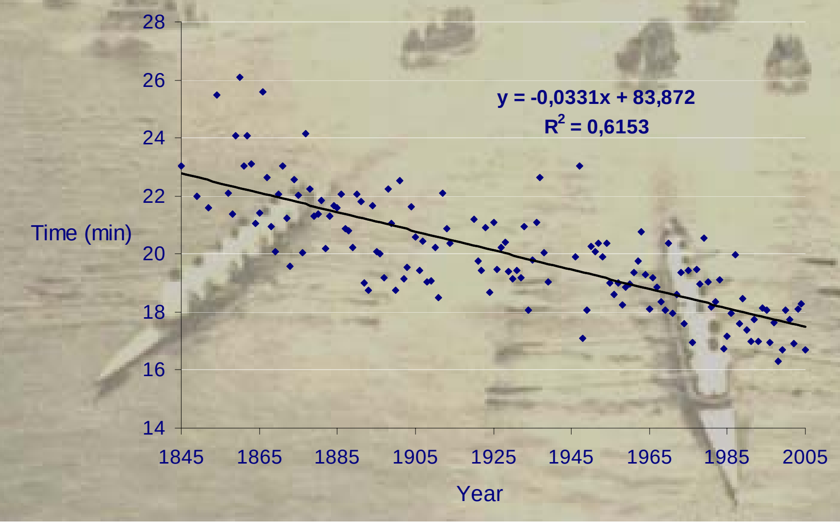
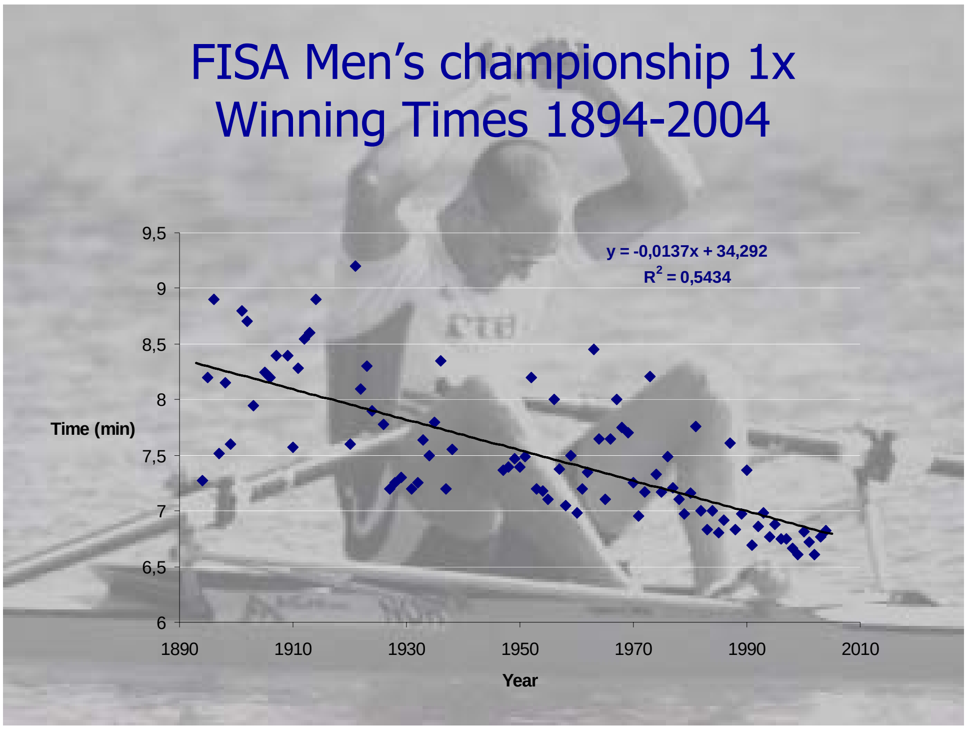


Oxford-Cambridge Boat Race

Winning Times 1845-2005

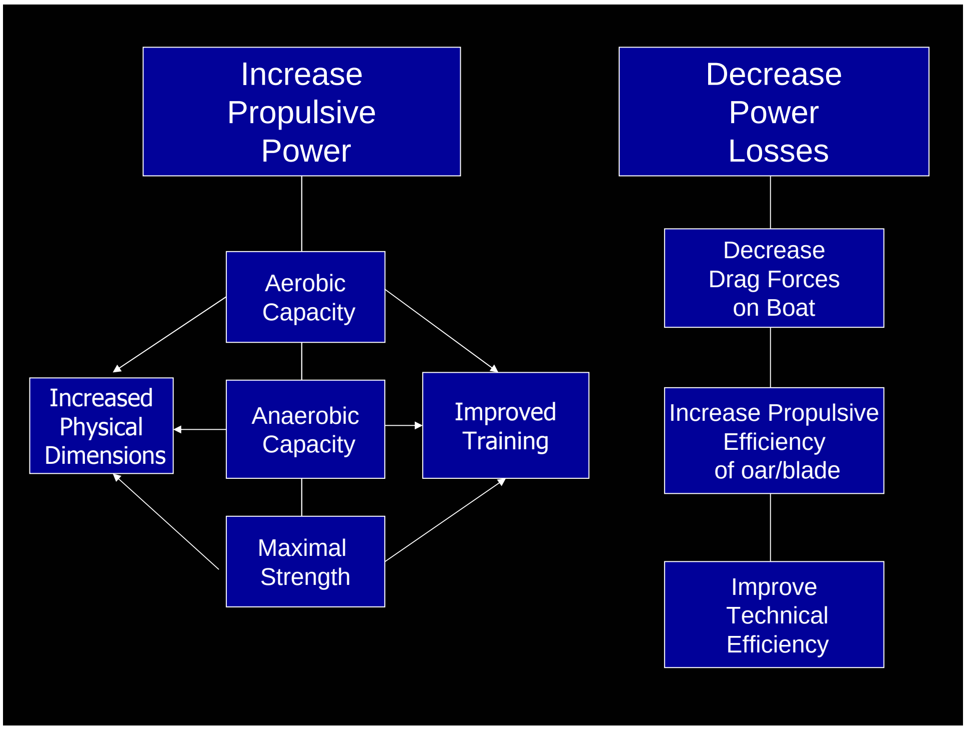




25-30% increase
in average velocity over 150 years
of competitive rowing

What are the performance variables and
how have they changed?

How will future improvements
be achieved?



"Evolutionary Constraints"

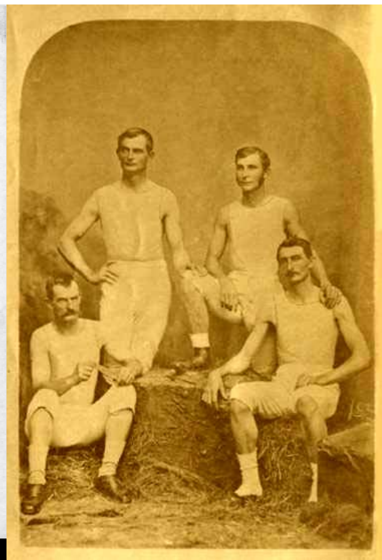
- Race duration ~ 6-8 minutes
- Weight supported activity
- Oar geometry dictates relatively low cycle frequency and favors large stroke distance to accelerate boat
- High water resistance decelerates boat rapidly between force impulses

These constraints result in:

- High selection pressure for height and arm length
- High selection pressure for *absolute* (weight independent) aerobic capacity
- Significant selection pressure for muscular strength and anaerobic capacity

Ned Hanlan ca 1880
173cm
71kg

Biglin Brothers ca 1865
180cm? 75-80kg?

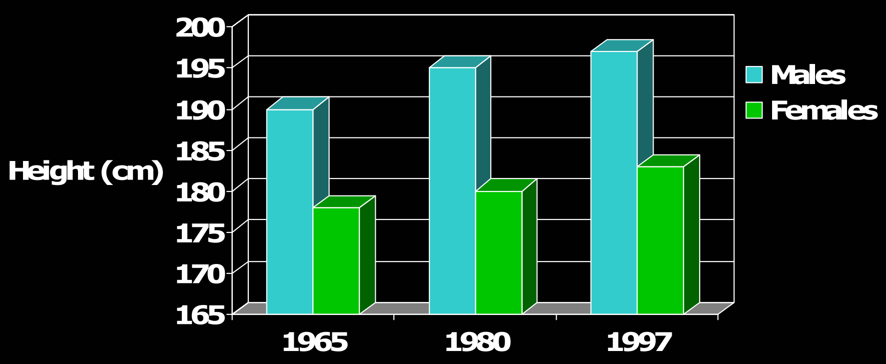


Ward Brothers ca 1865
185cm?
80+kg?

"Since the 19th century there have been clearly documented secular trends to increasing adult height in most European countries with current rates of 10-30mm/decade."

Cole, T.J. Secular Trends in Growth. Proceedings of the Nurition Society. 59, 317-324, 2000.

97th percentile for height in Dutch 21 year-olds



Redrawn after data from Fredriks et al, in Cole, T.J. Secular Trends in Growth. Proceedings of the Nutrition Society. 59, 317-324, 2000.

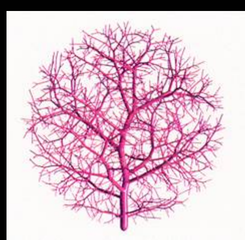
Taller Population= Taller Elite Rowers

Oxford Crew-2005
Average Height: 197cm
Average bodyweight
98.3 kg

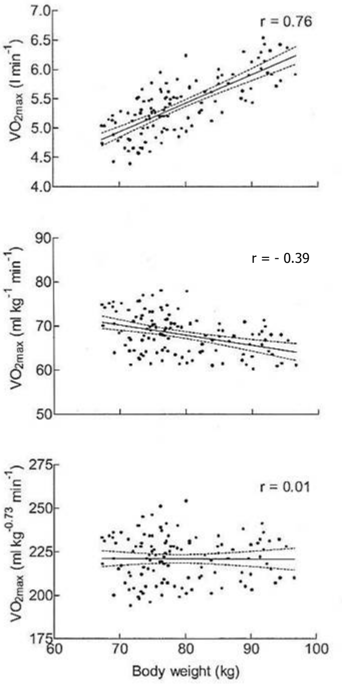
Scaling problems- Geometry or fractal filling volumes?

Based on Geometric scaling:
Strength and VO_2max will increase in proportion to **mass** $^{2/3}$.

BUT, Metabolic rates of organisms scale with **mass**$^{3/4}$.



See: West, G.B et al A general model for the origin of allometric scaling laws in biology. Science 276 122-126, 1997.



VO_2 body mass scaling in elite rowers

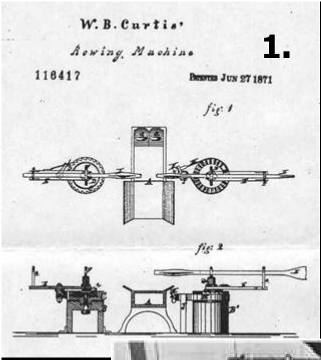
Relationship between maximal oxygen uptake and body mass for 117 Danish rowers (national team candidates)

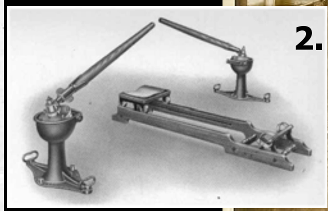
A key finding of this study was that VO2 scaled with body mass raised to the =.73 power, or close to the 0.75 value predicted by metabolic scaling

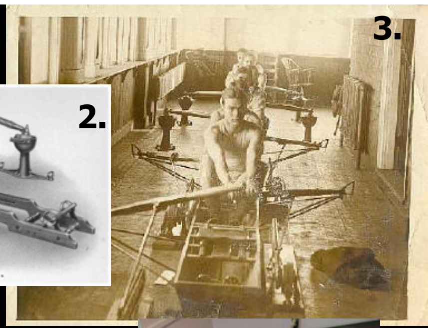
From: Jensen, K., Johansen, L, Secher, N.H. Influence of body mass on maximal oxygen uptake: effect of sample size. Eur. J. Appl. Physiol. 84: 201-205, 2001.

Measuring Rowing Specific Physical Capacity

Photo courtesy of Mathijs Hofmijster, Faculty of Human Movement Sciences, Free University Amsterdam, Netherlands







photos 1-4 from Miller, B. "The development of rowing equipment" http://www.rowinghistory.net/equipment.htm

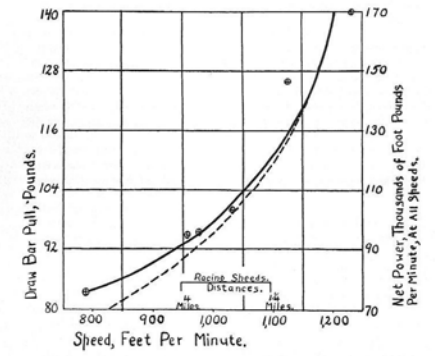
The Maximum of Human Power and its Fuel

From Observations on the Yale University Crew, Winner of the Olympic Championship, Paris, 1924

Crew average:

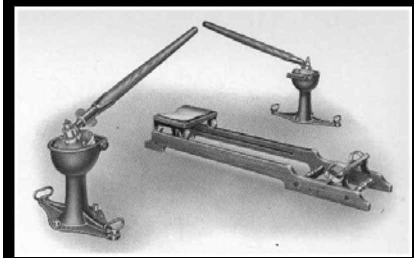
Height: 185 cm
Weight: 82 kg

Henderson, Y and Haggard, H.W. American J. Physiology. 72, 264-282, 1925



Estimated external work required at racing speed based on:

1. Boat pulling measurements
2. Work output on a rowing machine
3. Rowing ergometer VO_2 measurements (but did not go to max)



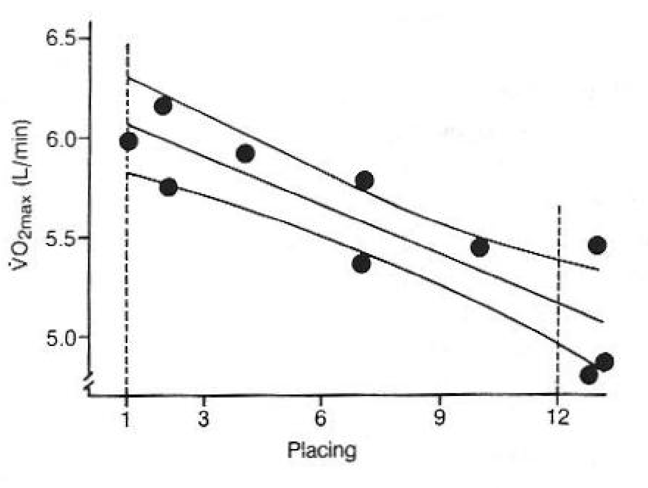
The ergometer of the day had to be redesigned to allow a quantification of work and power.

Estimated an external work requirement of ~6 Calories/min or (assuming 20% efficiency)
30 Calories/min energy expenditure.

Equals ~ 6 Liter/min O_2 cost

Assumed 4 L/min VO_2 max and 2 L/min anaerobic contribution during 6 min race.

1970s - VO_2 max vs boat placement in international regatta



Even if we assume 5 liter/min max for the dominant, champion 1924 crew, they would have been at the bottom of the international rankings 50 years later, as this team boat VO2 max data compiled by Secher demonstrates.

From Secher NH. Rowing. Physiology of Sports (ed. Reilly et al) pp 259-286. 1971

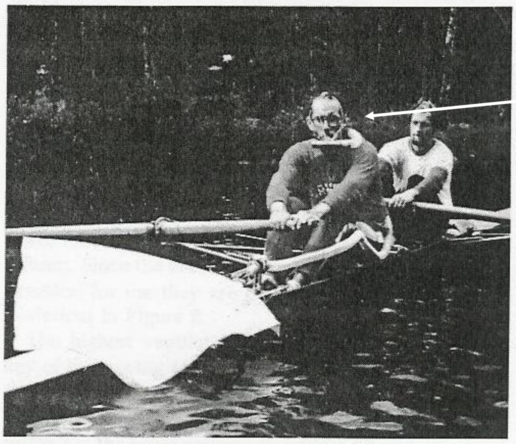


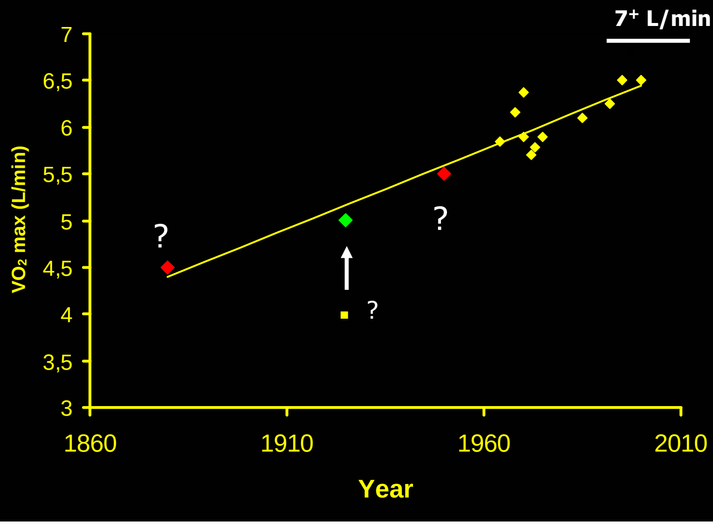
FIGURE 1—Gas collection apparatus in the coxless pair.

193 cm, 92 kg 6.23 L/min VO_2 cycling. Subject reached 6.1 to 6.4 L/min during repeated testing in different boats.

This study was unique because 1) on water measurements were made of champion rowers and, 2) the authors of the paper WERE the Champion rowers (Niels Secher, Denmark and Roger Jackson, Canada) who went on to very successful sport science careers.

Jackson, R.C. and N. H. Secher. The aerobic demands of rowing in two Olympic rowers. Med. Sci. Sports Exerc. 8(3): 168-170, 1976.

Aerobic Capacity Developments ?



Dr. Fred Hagerman
Ohio University

There is just not much data available prior to the late 60s, so the question marks emphasise that this is guessing. But that aerobic capacity has increased Is clear. Today, isolated 7 liter values VO2 max values have been recorded in several good laboratories for champion rowers.

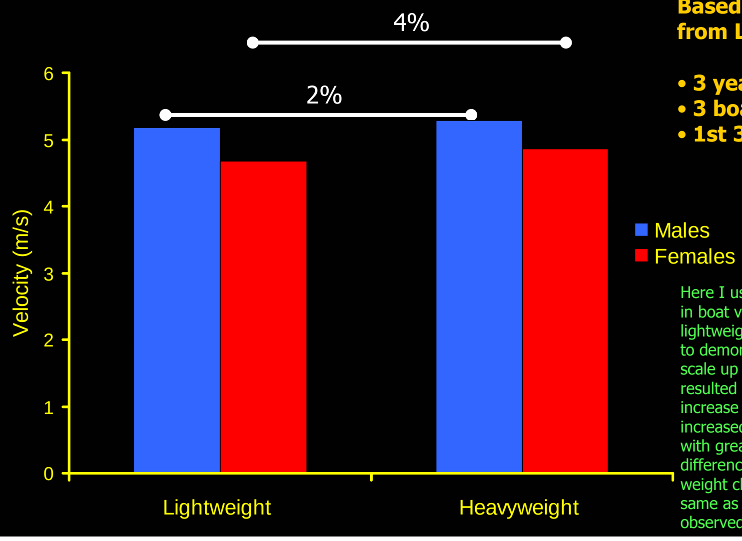
”Typical World Class”
XC skiers

6.3 L/min, 75 kg,
85 ml/kg/min
270 ml/kg$^{0.73}$/min

Allometrically equivalent rower?

7.5 L/min, 95kg, (do they exist?)
79 ml/kg/min,
270 ml/kg$^{0.73}$/min

How much of performance improvement is attributable to increased physical dimensions?



Based on W Cup results from Lucerne over:

- **3 years**
- **3 boat types**
- **1st 3 places**

Here I use present day differences in boat velocity for world class lightweight and heavyweight crews to demonstrate that the massive scale up in body size has not resulted in a proportional increase in boat speed, due to increased power losses associated with greater boat drag. The difference between these two weight classes today is about the same as the increase in body size observed over 150 years

TRAINING, IN THEORY AND PRACTICE.

BY ARCHIBALD MACLAREN.

London: MACMILLAN AND CO.

A Day's Training.

Rise at 7 a.m: Run 100-200 yards as fast as possible

	Tea, two cups, or towards the end of training a cup and a half only. Watercresses occasionally.	
Exercise (forenoon).	None.	
Dinner about 2 p.m.	Meat, Beef or Mutton. Bread. Vegetables — Potatoes, Greens.	Some Colleges have baked Apples, or Jellies, or Rice-

About 5:30: Start for the river and row for the starting post and back

	Watercresses.	
Bed at 10.0	Beer, one pint.	

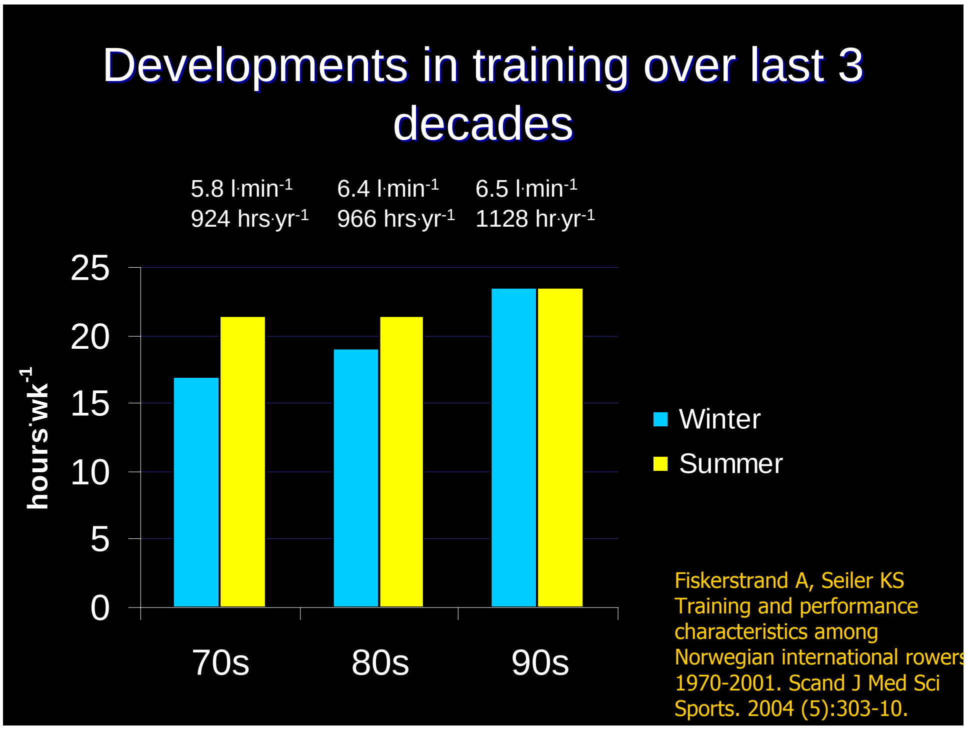
Reckoning a half an hour in rowing to and half an hour from the starting point, and a quarter of an hour for the morning run- in all, say, one and a quarter hours.

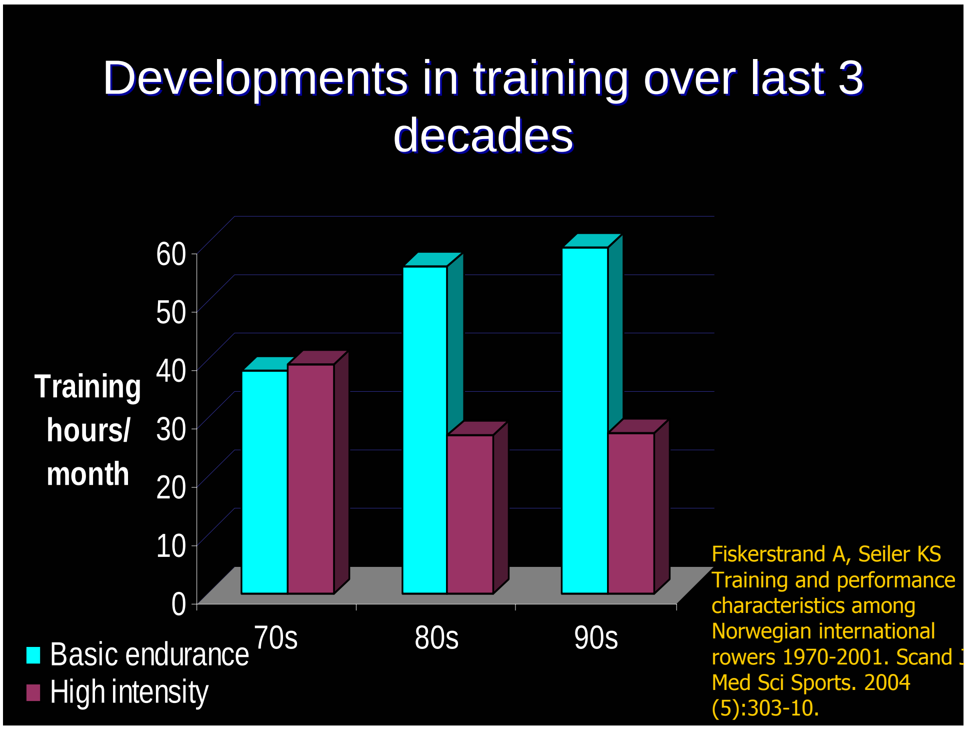
Mon	8:00	Weights	120 min	
	10:00	Row	70 min Steady state in pairs	HR 144-148
	4:00	Row	100 min Steady state in pairs	HR 140-144
Tues	8:00	Row	2 x 5x5 min ON/1 min OFF in pairs	HR 180-185
	10:30	Erg	12 kilometers	HR 150
	4:00	Row	100min Steady state in eight	
Wed	8:00	Weights	120 min	
	10:00	Run	3 x 10 laps	160-175
	4:00	Row	100min steady in eight	140-148
Thurs	8:00	Row	2 sets 12 x 20 power strokes in eight	
	10:30	Erg	75 min (about 17500m)	140-148
	4:00	Erg	3 x 20 min	140-148
Fri	8:00	Weights	120 min	
	10:30	Erg	15 km	140-160
	3:30	Row	90 min steady state in eight	144-170
Sat	9:00	Row	90 min steady state in eight	140-160
	3:00	Row	90 min steady state in four	144-170
Sun	9:00	Row	3 sets 4 x 4 min ON/1 min OFF in pairs	180-190

US National Team training during peak loading period

3 sessions/day
30+ hr/wk

From US Women's national team 1996


Developments in training over last 3 decades
5.8 l·min-1
924 hrs·yr-1
6.4 l·min-1
966 hrs·yr-1
6.5 l·min-1
1128 hr·yr-1
hours·wk-1
25
20
15
10
5
0
70s
80s
90s
Winter
Summer
Fiskerstrand A, Seiler KS
Training and performance characteristics among Norwegian international rowers 1970-2001. Scand J Med Sci Sports. 2004 (5):303-10.


Developments in training over last 3 decades
Training hours/ month
60
50
40
30
20
10
0
70s
80s
90s
Basic endurance
High intensity
Fiskerstrand A, Seiler KS
Training and performance characteristics among Norwegian international rowers 1970-2001. Scand J Med Sci Sports. 2004 (5):303-10.

1860s - "Athletes Heart" debate begins

- 1867- London surgeon F.C. Shey likened The Boat Race to cruelty to animals, warning that maximal effort for 20 minutes could lead to permanent injury.
- 1873- John Morgan (physician and former Oxford crew captain) compared 251 former oarsmen with non-rowers -concluded that the rowers had lived 2 years longer!
- Myocardial hypertrophy was key topic of debate, but tools for measurement (besides at autopsy) were not yet available.

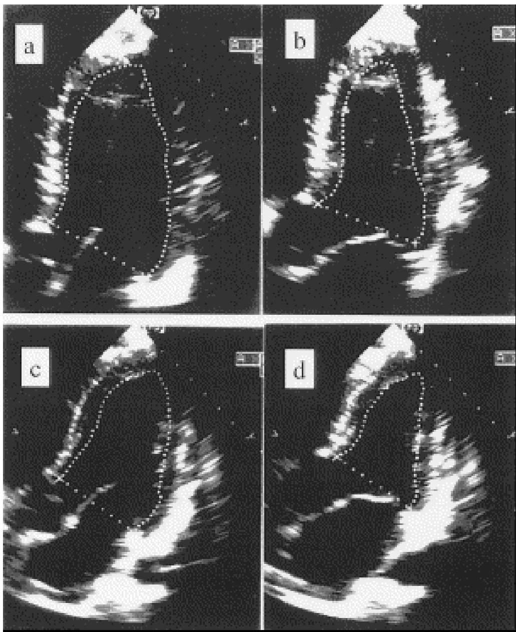
See: Park, R.J. High Protein Diets, "Damaged Hearts and Rowing Men: antecendents of Modern Sports Medicine and Exercise Science, 1867-1928. Exercise and Sport Science Reviews, 25, 137-170, 1997.

See also: Thompson P.D. Historical aspects of the Athletes Heart. MSSE 35(2), 364-370 2003.

Big-hearted Italian Rowers - 1980s

- Of 947 elite Italian athletes tested, 16 had ventricular wall thicknesses exceeding normal criteria for cardiomyopathy. 15 of these 16 were rowers or canoeists (all international medalists).
- Suggested that combination of pressure and volume loading on heart in rowing was unique, but adaptation was physiological and not pathological.

from: Pelliccia A. et al. The upper limit of physiologic cardiac hypertrophy in highly trained elite athletes. New England J. Med. 324, 295-301, 1991.

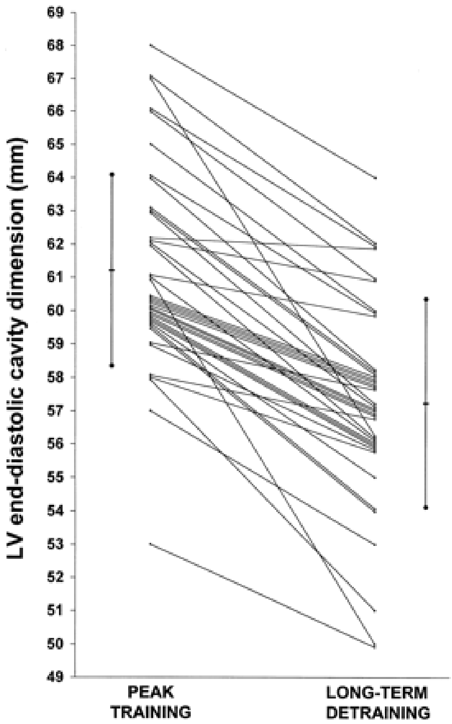


elite rower

These ultrasound images show the hypertrophied but geometrically similar heart of an elite Italian rower compared to the smaller heart of an untrained subject.

untrained control

From: Pelliccia et al. Global left ventricular shape is not altered as a consequence of physiologic remodelling in highly trained athletes. Am. J. Cardiol. 86(6), 700-702, 2000



Myocardial adaptation to heavy endurance training was shown to be reversed with detraining.

The functional and morphological changes described as the "Athlete's Heart" are adaptive, not pathological.

Pelliccia et al. Remodeling of Left Ventricular Hypertrophy in Elite Athletes After Long-Term Deconditioning *Circulation.* 105:944, 2002

Force production and strength in rowing

- Ishiko used strain gauge dynamometers mounted on the oars of the silver medal winning 8+ from Tokyo 1964 to measure peak dynamic forces.
- Values were of the magnitude 700-900 N based on the figures shown

Photo from WEBA sport GMBH

Ishiko, T. Application of telemetry to sport activities. *Biomechanics.* 1:138-146, 1967.

How Strong do Rowers need to be?

1971 - Secher calculated power to row at winning speed in 1972 championships = 450 watts (2749 kpm/min)

"In accordance with the force-velocity relationship a minimal (isometric) rowing strength of 53 ÷ 0.4 = 133 kp (1300N) will be essential."

From: Secher, N.H. Isometric rowing strength of experienced and inexperienced oarsmen. Med. Sci. Sports Exerc.7(4) 280-283, 1975.

Force production and rowing strength

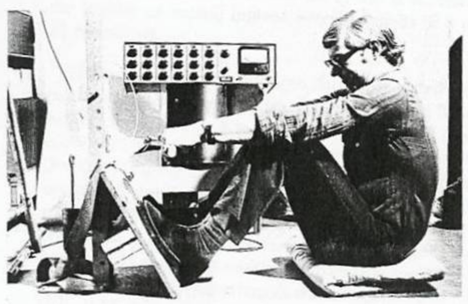


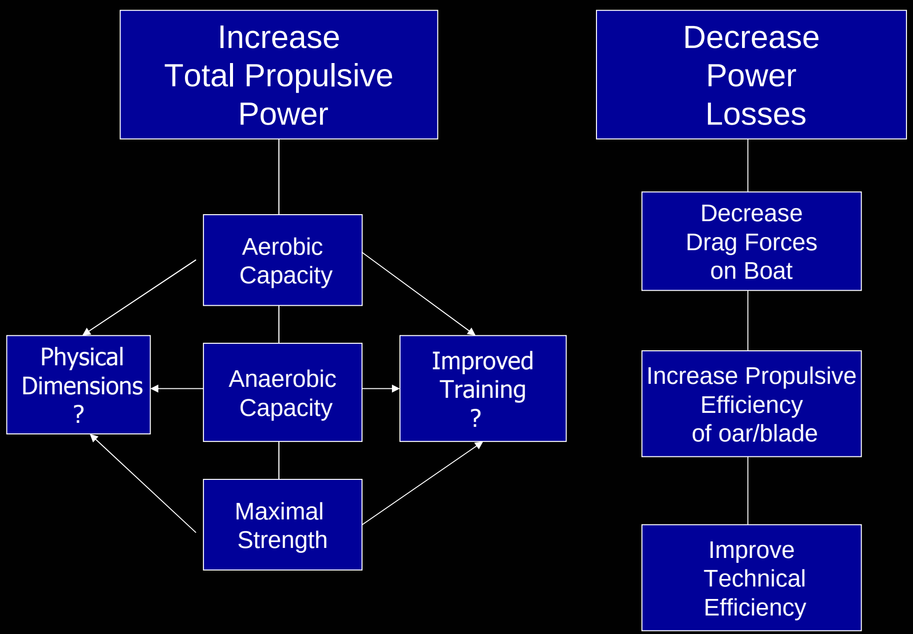
Figure 1—Apparatus and set-up for determination of rowing strength.

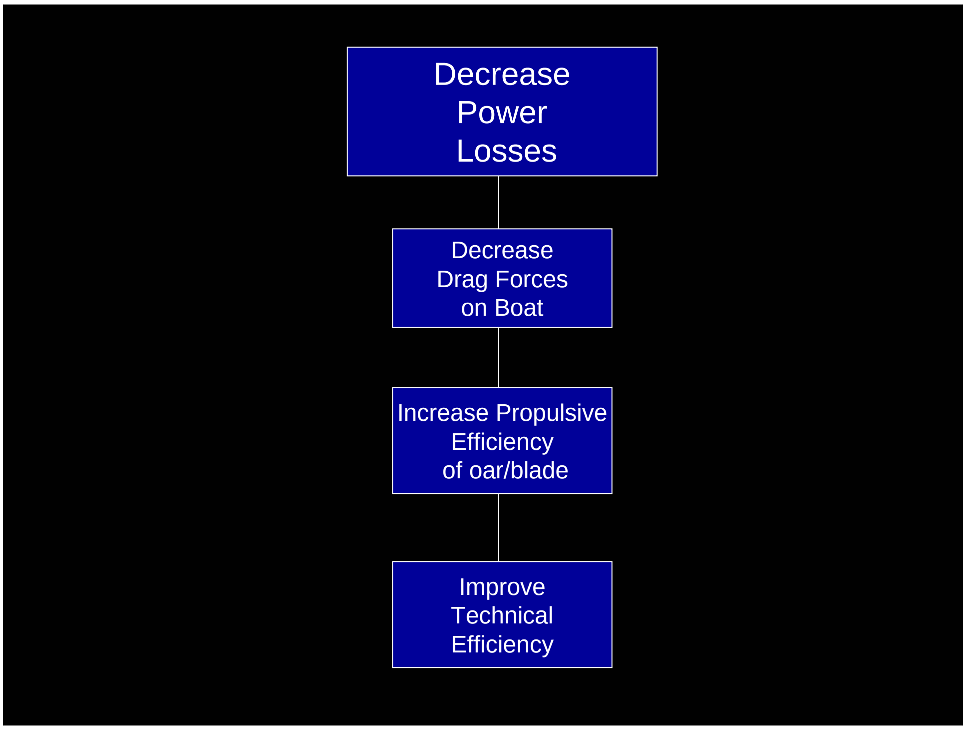
From: Secher, N.H. Isometric rowing strength of experienced and inexperienced oarsmen. Med. Sci. Sports Exerc.7(4) 280-283, 1975.

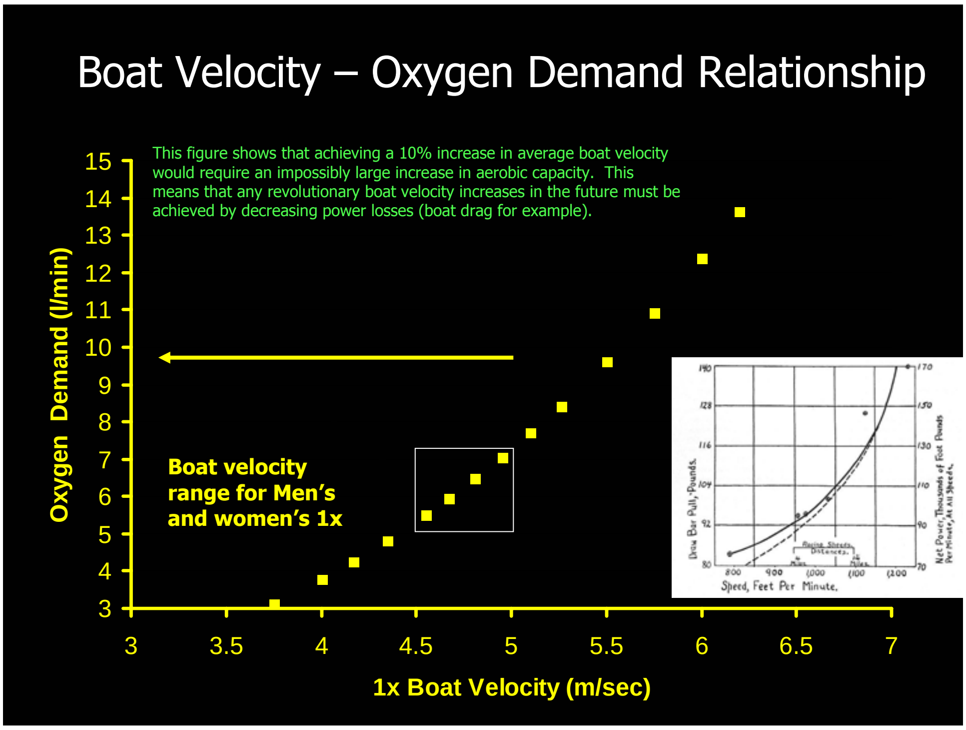
Measured isometric force in 7 Olympic/world medalists, plus other rowers and non-rowers

Average peak isometric force (mid-drive): **2000 N** in medalists

NO CORRELATION between ”rowing strength” and leg extension, back extension, elbow flexion, etc.

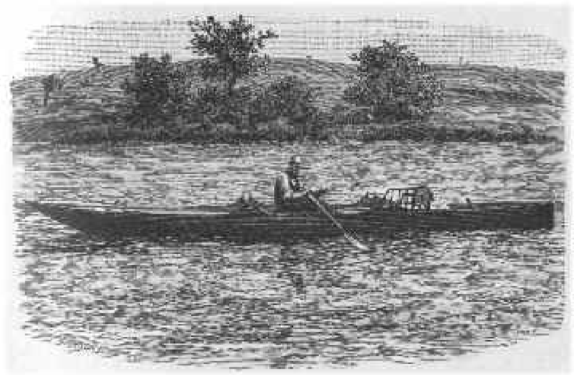



Decrease Power Losses
Decrease Drag Forces on Boat
Increase Propulsive Efficiency of oar/blade
Improve Technical Efficiency


Boat Velocity – Oxygen Demand Relationship
This figure shows that achieving a 10% increase in average boat velocity would require an impossibly large increase in aerobic capacity. This means that any revolutionary boat velocity increases in the future must be achieved by decreasing power losses (boat drag for example).
Oxygen Demand (l/min)
15
14
13
12
11
10
9
8
7
6
5
4
3
Boat velocity range for Men's and women's 1x
3
3.5
4
4.5
5
5.5
6
6.5
7
1x Boat Velocity (m/sec)
Speed, Feet Per Minute.

Drag Forces on the Boat and Rower

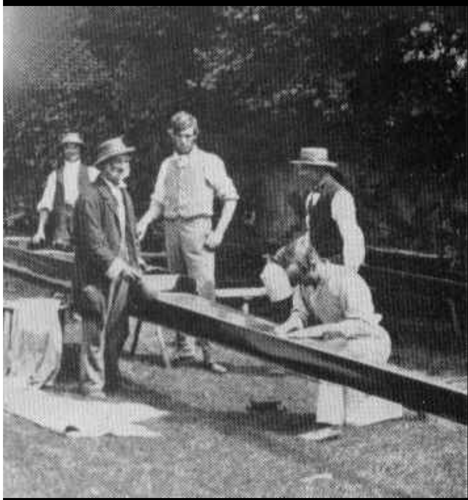
- Boat Surface Drag - 80% of hydrodynamic drag (depends on boat shape and total wetted surface area)
- Wave drag contribution small - <10% of hydrodynamic drag
- Air resistance – normally <10% of total drag, depends on cross-sectional area of rowers plus shell



In-rigged wherry typical of those used in racing prior to 1830

figures from Miller, B. "The development of rowing equipment"
http://www.rowinghistory.net/equipment.htm

All radical boat form improvements completed by 1856.



- 1828-1841. Outrigger tried by Brown and Emmet, and perfected by Harry Clasper
- Keel-less hull developed by William Pocock and Harry Clasper 1840-1845
- Thin-skin applied to keel-less frame by Matt Taylor- 1855-56
- **Transition to epoxy and carbon fiber boats came in 1972. Boat weight of 8+ reduced by 40kg**

photo and timeline from Miller, B. "The development of rowing equipment" http://www.rowinghistory.net/equipment.htm

Effect of reduction in Boat Weight on boat velocity

$$\Delta V/V = -(1/6)\ \Delta\ M/M_{total}$$

Example: Reducing boat+oar weight from 32 to 16kg = 2.4% speed increase for 80 kg 19th century rower.

V= boat velocity
M = Mass
ΔV= Change in Velocity
ΔM= Change in Mass

From: Dudhia, A Physics of Rowing.
http://www-atm.physics.ox.ac.uk/rowing/physics/

To achieve a radical reduction in drag forces on current boats, they would have to be lifted out of the water!

To run this video, download it to the same directory from http://sportsci.org/2006/flyak.wmv (7.4 MB)

Video of a hydrofoil kayak with two submerged wings. See http://www.foilkayak.com/

Decrease Power Losses

Decrease Drag Forces on Boat

Increase Propulsive Efficiency of oar/blade

Improve Technical Efficiency

Oar movement translates rower power to boat velocity

Boat Travel

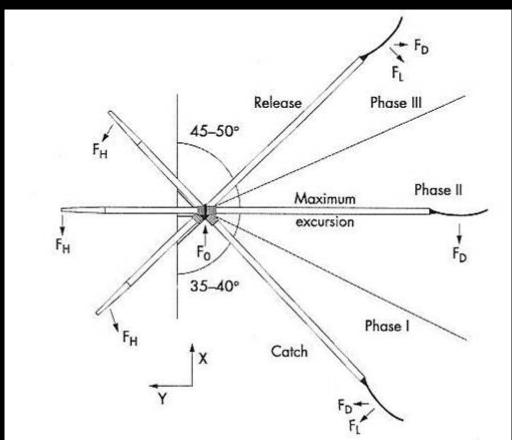
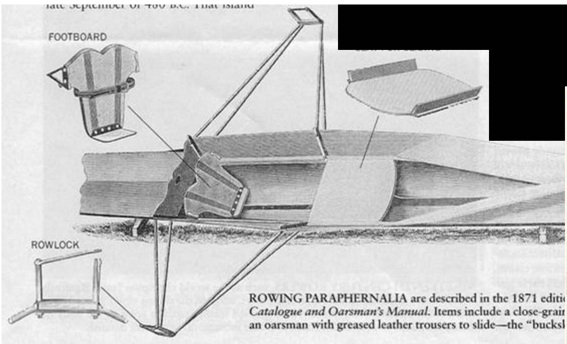
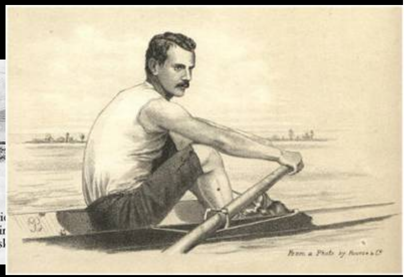


Figure from:

Baudouin, A. & Hawkins D.
A biomechanical review of factors affecting rowing performance. British J. Sports Med. 36: 396-402

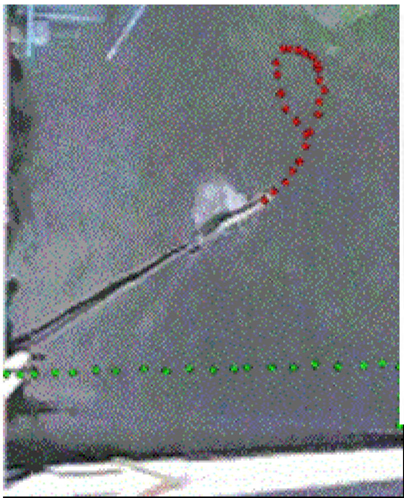


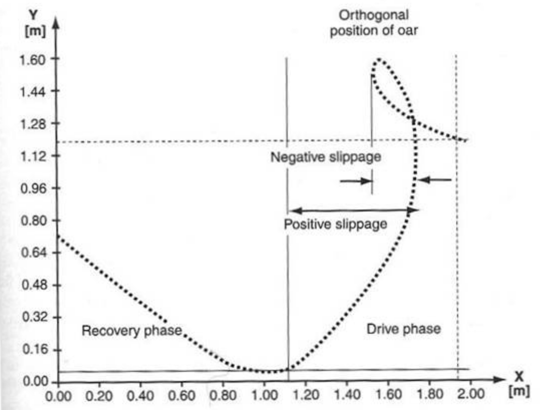


The slide properly used is a decided advantage and gain of speed, and only objection to its use is its complication and almost impracticable requirement of skill and unison in the crew, rather than any positive defect in its mechanical theory.

J.C. Babcock 1870

1876 Centennial Regatta, Philadelphia, Pennsylvania. London Crew winning heat





From: Nolte, V. Die Effektivitat des ruderschlages. 1984
in: Nolte, V ed. Rowing Faster. Human Kinetics, 2005

Boat direction

A common conception of the oar blade-water connection is that it is solid, but it is not. Water is moved by the blade. Energy is wasted in moving water instead of moving the boat as the blade "slips" through the water. Much or oar development is related to improving blade efficiency and decreasing this power loss. However, the improvement has been gradual, in part due to technological limitations in oar construction.

Photo from www.concept2.com

Oar hydrodynamic efficiency- propelling the boat but not the water

$$E_{hydro} = \frac{\text{Power applied}_{rower} - \text{Power loss}_{moving\ water}}{\text{Power applied}_{rower}}$$

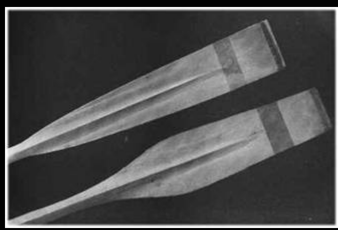
Power applied = Force Moment at the oar * oar angular velocity

Oar power loss = blade drag force * *blade velocity (slip)*

Affeld, K., Schichl, Ziemann, A. Assessment of rowing efficiency Int. J. Sports Med. 14 (suppl 1): S39-S41, 1993.

Oar Evolution

Square loomed scull 1847

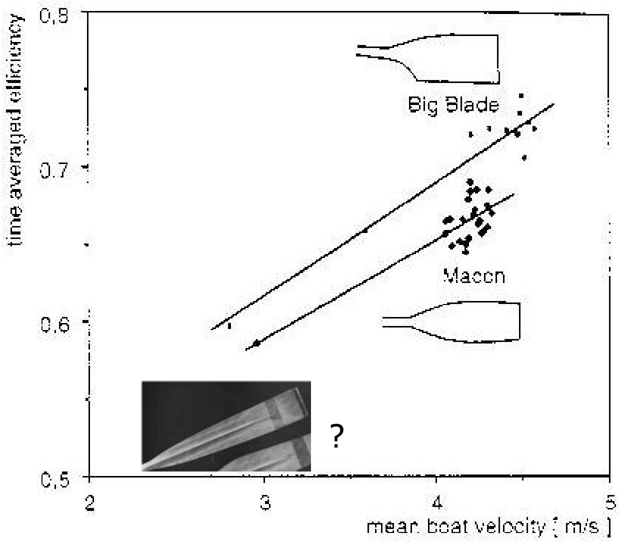


"Square" and "Coffin" blades 1906

Macon blade-wooden shaft 1960-1977

Macon Blade- carbon fiber shaft 1977-1991

Cleaver blade – ultra light carbon fiber shaft 1991-

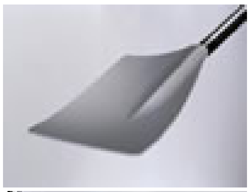


Big blades found to be 3% more hydrodynamically efficient compared to Macon blade

Affeld, K., Schichl, Ziemann, A. Assessment of rowing efficiency Int. J. Sports Med. 14 (suppl 1): S39-S41, 1993.

Rower/tinkerer/scientists?- The Dreissigacker Brothers

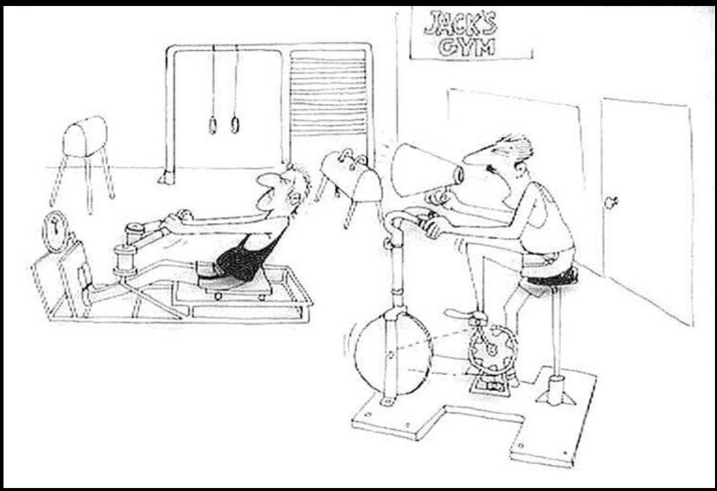
All pictures from www.concept2.com in exchange for unsolicited and indirect endorsement!



Effect of Improved Oars on boat speed?

- Kleshnev (2002) used instrumented boats and measurement of 21 crews to estimate an 18% energy loss to moving water by blade
- Data suggests 2-3% gain in boat velocity possible with further optimization of oar efficiency (30-50% of the present ~ 6 % velocity loss to oar blade energy waste)

Rowing Technique: "Ergs don't float"

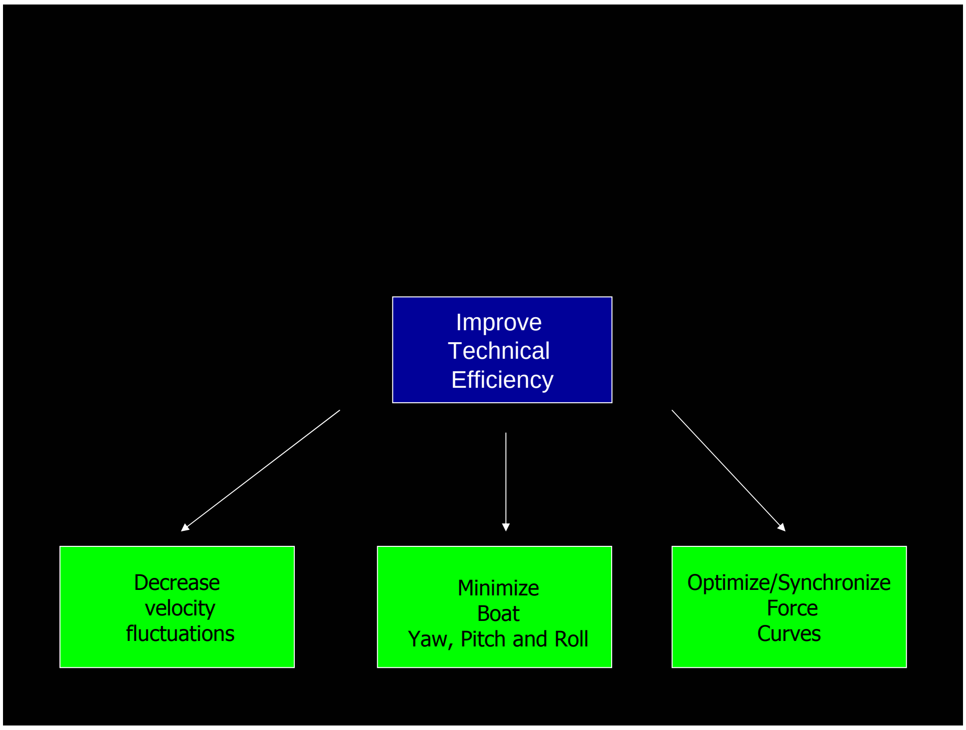


Decrease Power Losses

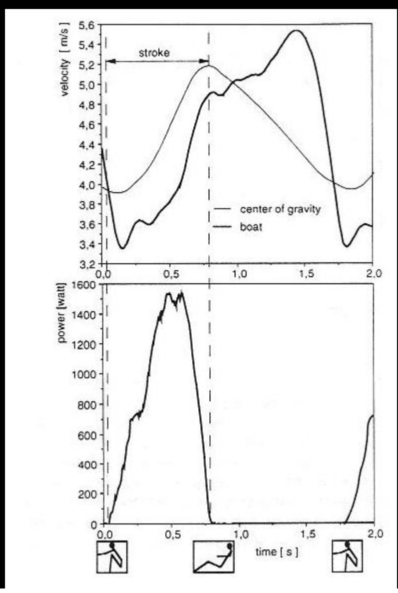
Decrease Drag Forces on Boat

Increase Propulsive Efficiency of oar/blade

Improve Technical Efficiency



Decreasing Velocity Fluctuations



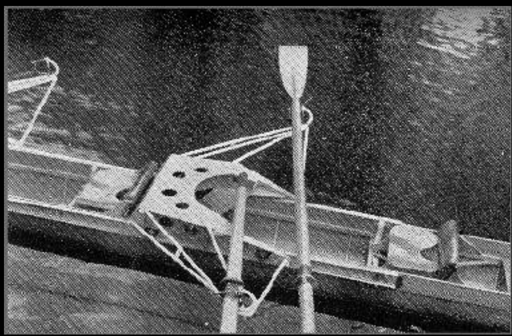
Sources

- Pulsatile Force application
- Reactions to body mass acceleration in boat

Larger fluctuations require greater propulsive power for same average velocity

Figure from Affeld et al. Int. J. Sports Med. 14: S39-S41, 1993

The Sliding Rigger



1954 Sliding Rigger developed by C.E. Poynter (UK)

- Idea patented in 1870s
- Functional model built in 1950s
- Further developed by Volker Nolte and Empacher in early 1980s
- Kolbe won WCs in 1981 with sliding rigger
- Top 5 1x finalists used sliding rigger in 1982.
- Outlawed by FISA in 1983.

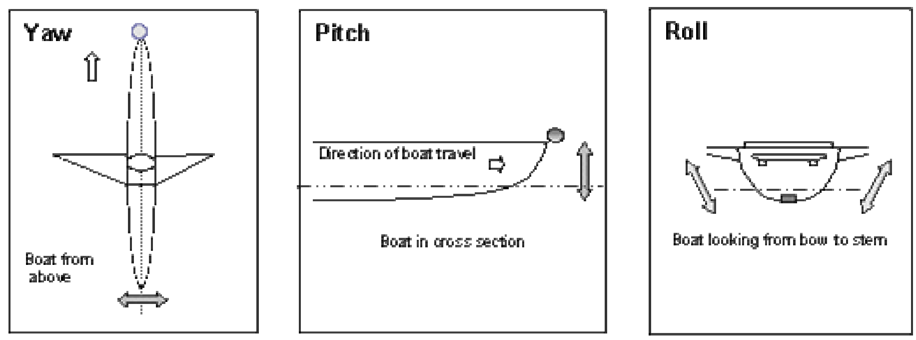
The sliding rigger was outlawed on the basis of its high cost (an unfair advantage). This argument would not be true today with modern construction methods.

From: Miller, B. The development of Rowing Equipment. http://www.rowinghistory.net

How much speed could be gained by reducing velocity fluctuations by 50%?

- Estimated ~5% efficiency loss due to velocity fluctuations (see Sanderson and Martindale (1986) and Kleshnev (2002)
- Reducing this loss by 50% would result in a gain in boat velocity of ~ 1% or ~4 seconds in a 7 minute race.
- **Sliding rigger effect probably bigger!** due to decreased energy cost of rowing and increased stability (an additional 1%+ ?)

Better Boat Balance?



0.1 to 0.6 degrees.
0.5 degrees = 2.5 cm bow movement

0.3 to 0.5 degrees
50% of variability attributable to differences in rower mass

0.3 to 2.0 degrees.
Highest variability between rowers here

Smith, R. Boat orientation and skill level in sculling boats. Coaches Information Service http://coachesinfo.com/

The Rowing Stroke Force Curve- A unique signature

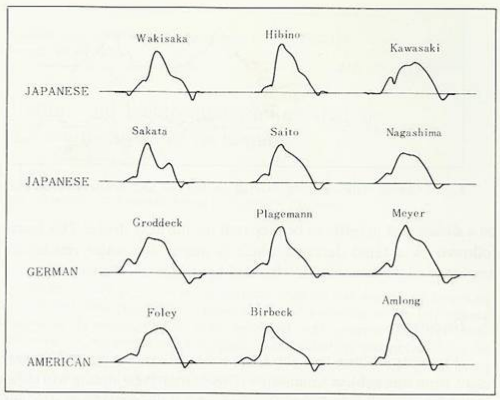
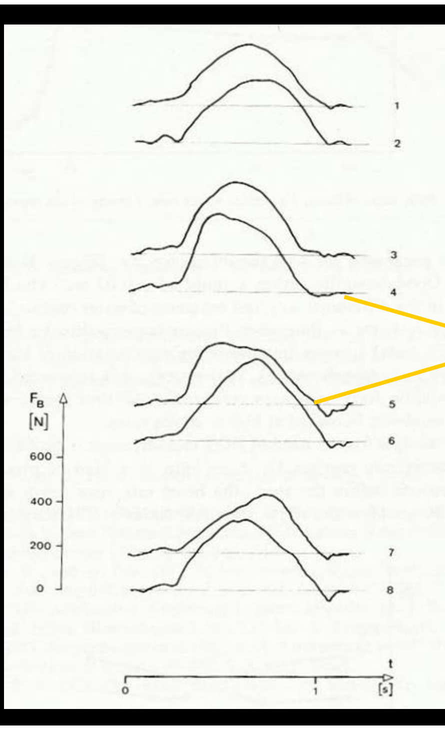


Fig. 2. Examples of force-time curves measured at the oar, by Japanese, German and American oarsmen.

"Oarsmen of a crew try to row in the same manner and they believe that they are doing so. But from the data it may be concluded that this is actually not true."

From: Ishiko, T. Biomechanics of Rowing. *Medicine and Sport volume 6: Biomechanics II*, 249-252, Karger, Basel 1971



A ”Good Crew”

Rowers 1 and 2 have very similar force curves, showing that the timing of blade forces in the two rowers is well matched. Rowers 3 and 4 are quite different from 1 and 2, reaching peak force earlier in their stroke. They are similar to each other though, perhaps explaining their ”visible success”. Rowers 7 and 8 show markedly different stroke force profiles, with rower 7 reaching peak force late in the stroke.

”A new crew with visible success”

2 juniors with ”only 1 year experience in the same boat”

From Schneider, E., Angst, F. Brandt, J.D. Biomechanics of rowing. In: Asmussen and Jørgensen eds. Biomechanics VI-B Univ. Park Press, Baltimore, 1978. pp 115-119.

Rowing Together: Synchronizing force curves

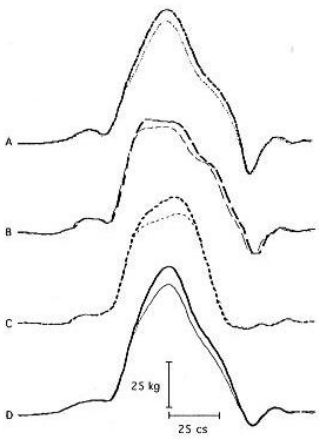


Figure 4 Ensemble-averaged ($n = 30$) force–time profiles for rowers A–D over two epochs, the second (faint line) some 3 min later than the first (bold line).

Fatigue changes the amplitude of the curve, but not its shape.

Changing rowers in the boat did not change the force curves of the other rowers, at least not in the short term.

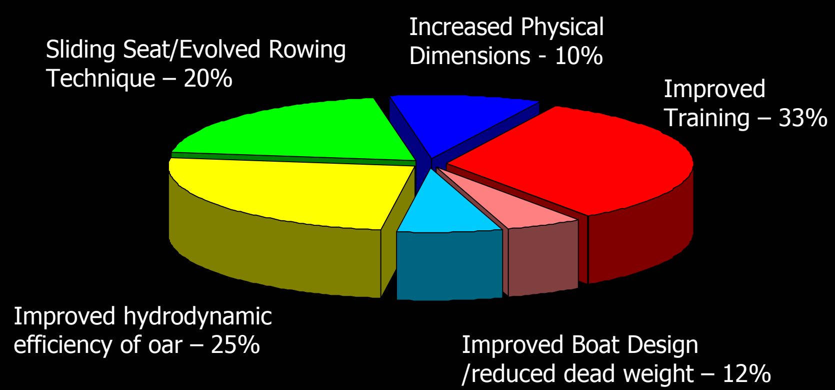
From: Wing, A.M. and Woodburn, C. The coordination and consistency of rowers in a racing eight. Journal of Sport Sciences. 13, 187-197, 1995

Is there an optimal force curve?

- For a 1x sculler: perhaps yes, one that balances hydrodynamic and physiological constraints to create a personal optimum.
- For a team boat: probably no single optimum exists due to interplay between biomechanical and physiological constraints at individual level.

see also: Roth, W et al. Force-time characteristics of the rowing stroke and corresponding physiological muscle adaptations. Int. J. Sports Med. 14 (suppl 1): S32-S34, 1993

Contribution of rowing variables to increased velocity over 150 years



This is my best estimate of the relative contribution of the different performance variables addressed to the development of boat velocity over 150 years. Future improvements are probably best achieved by further developments in oar efficiency, and perhaps the return of the sliding rigger!

This is Oxford. They won.

Thank You!

This is Cambridge. They…didn't.