150 Years of Rowing Faster!

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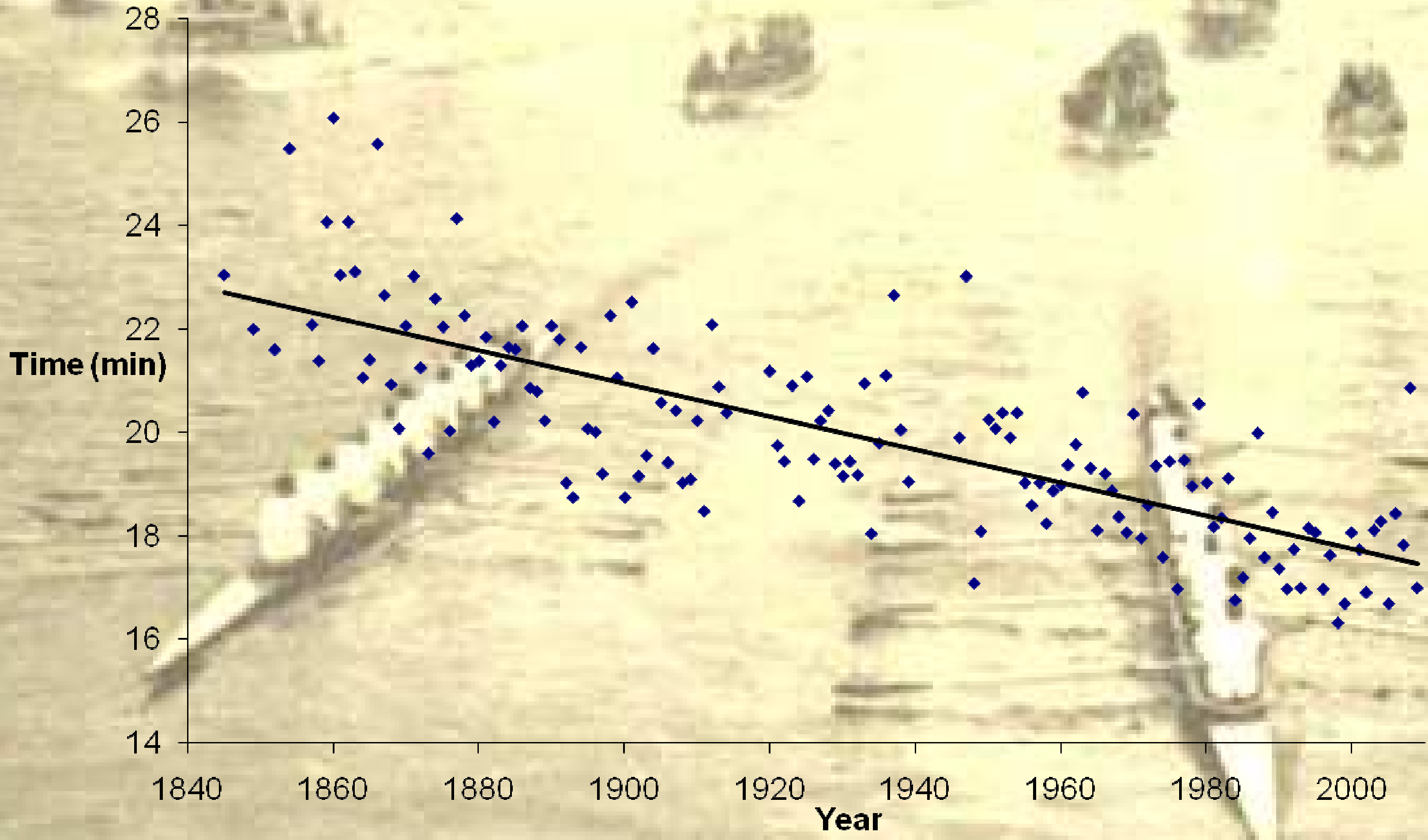
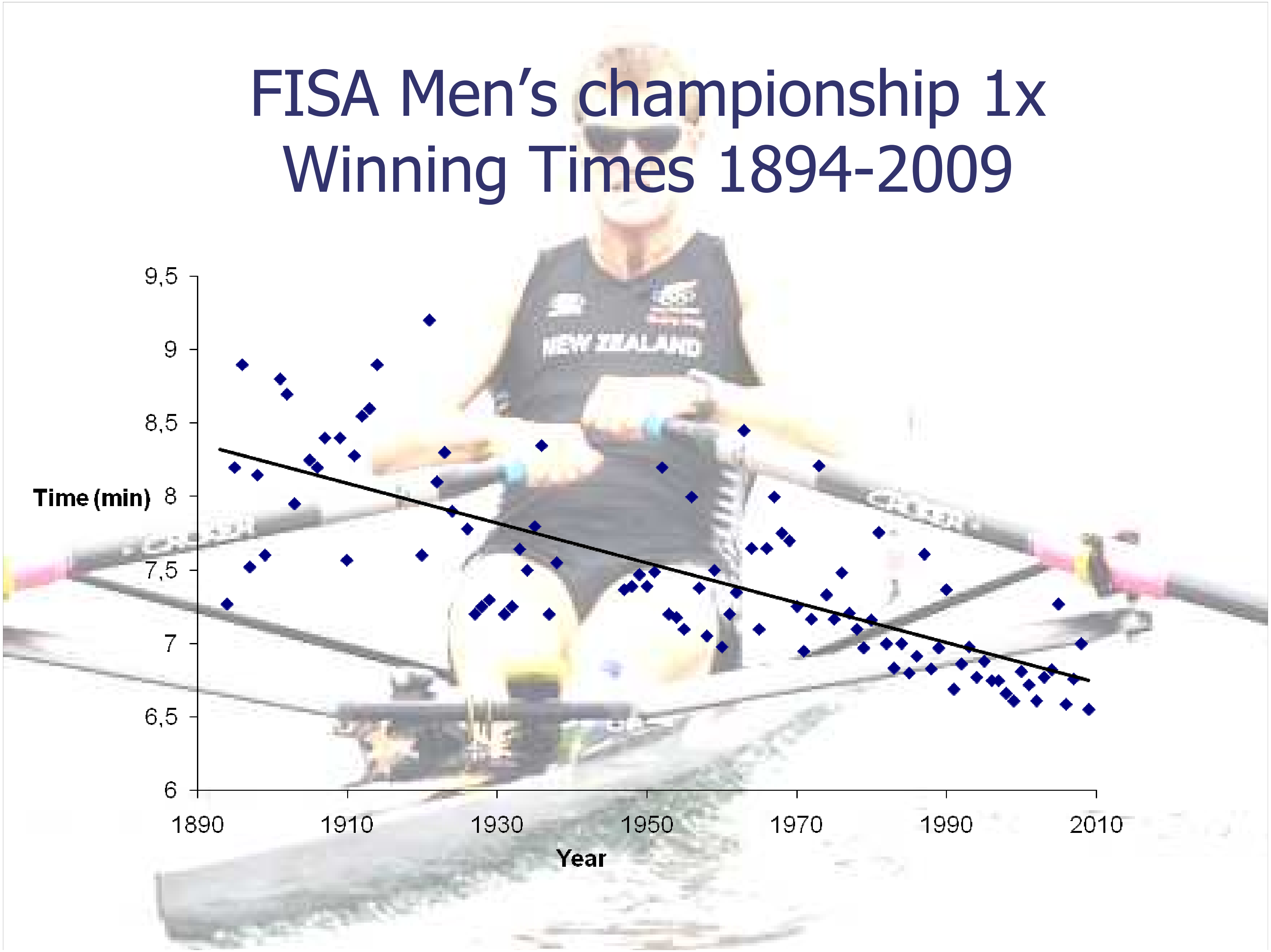
Oxford-Cambridge Boat Race

Winning Times 1845-2009



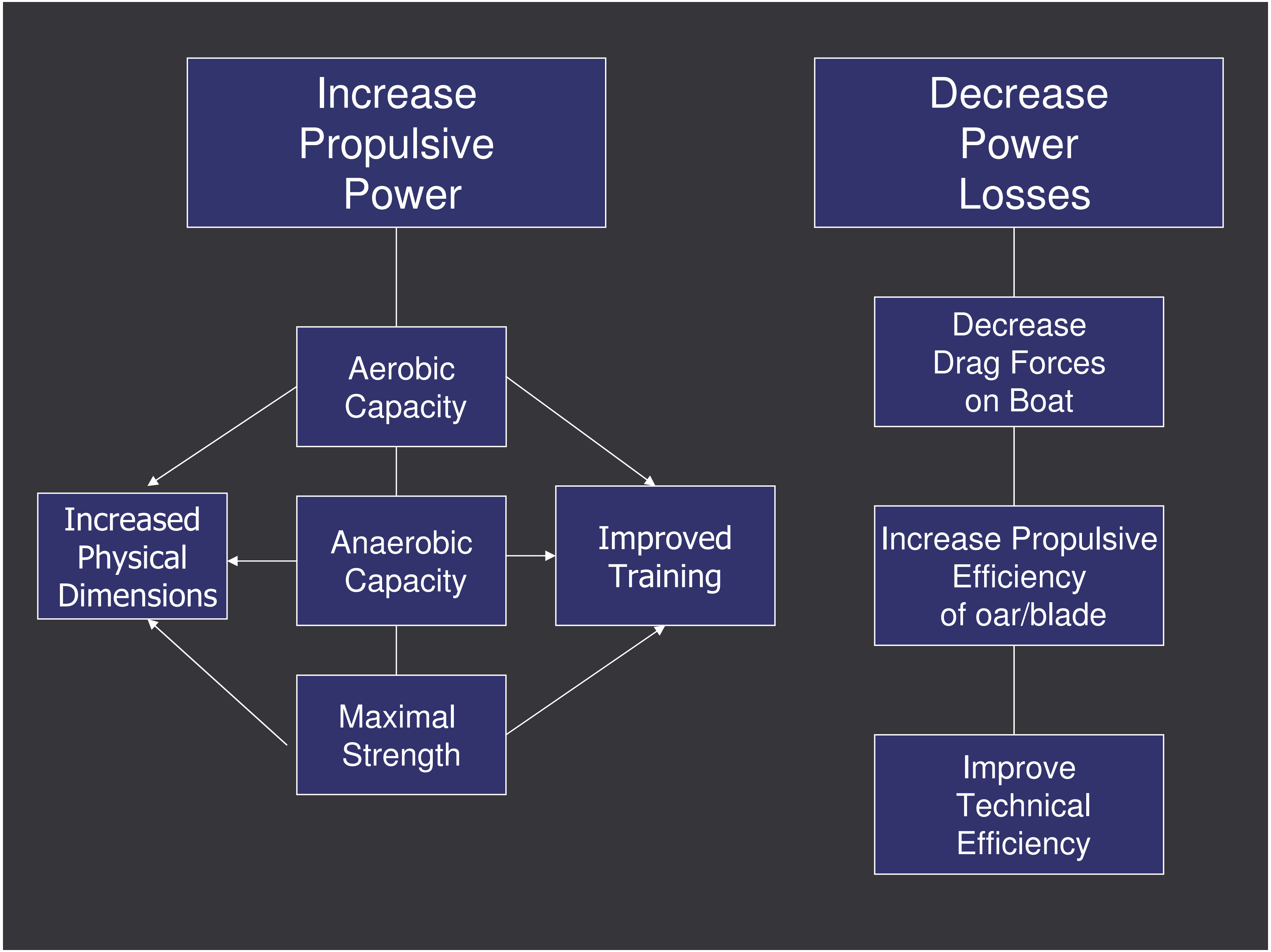
FISA Men's championship 1x Winning Times 1894-2009

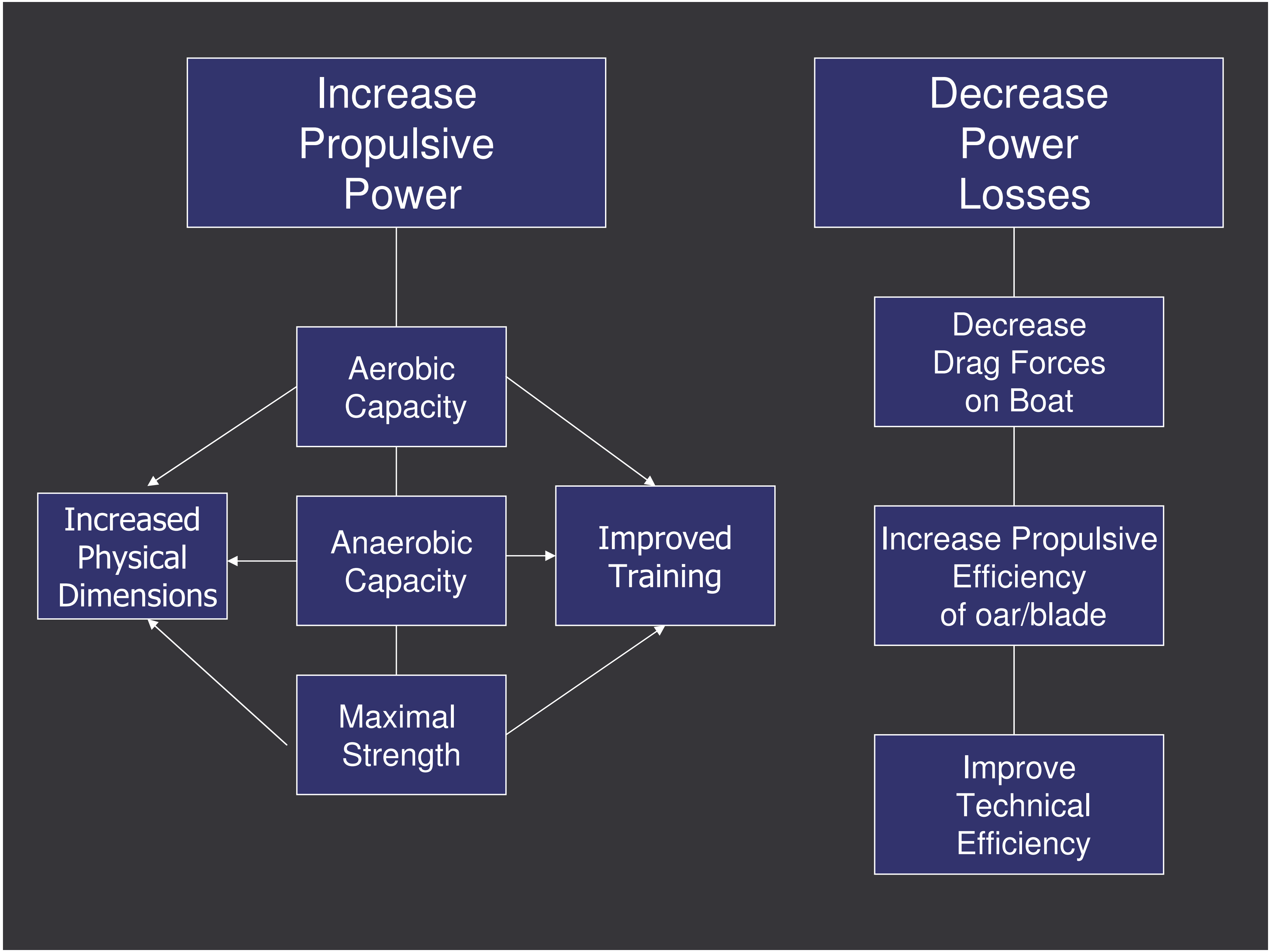


25-30% increase
in average velocity over 150 years
of competitive rowing

What are the performance variables and how have they changed?

How will future improvements be achieved?


Increase Propulsive Power
Aerobic Capacity
Increased Physical Dimensions
Anaerobic Capacity
Improved Training
Maximal Strength
Decrease Power Losses
Decrease Drag Forces on Boat
Increase Propulsive Efficiency of oar/blade
Improve Technical Efficiency



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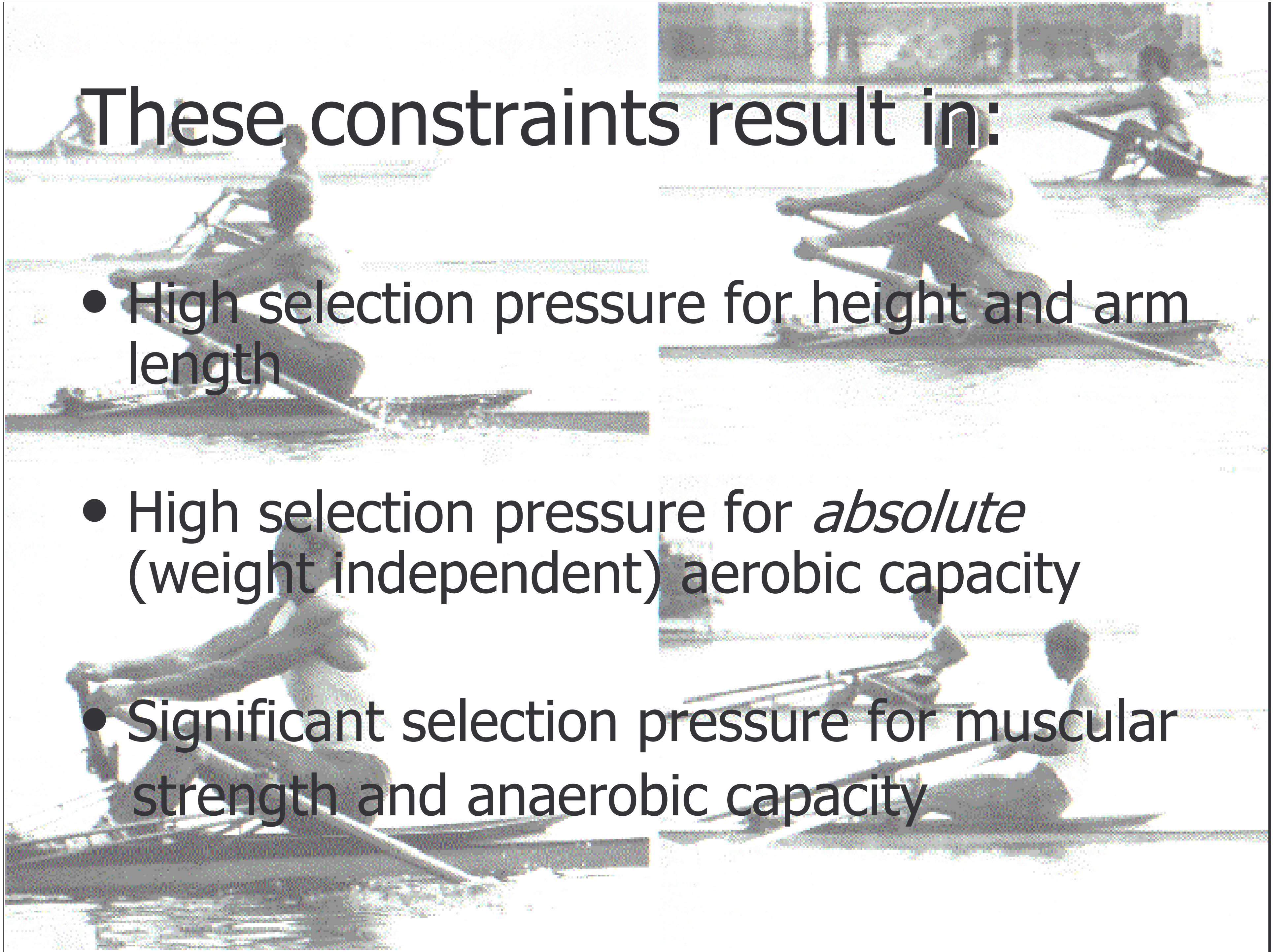
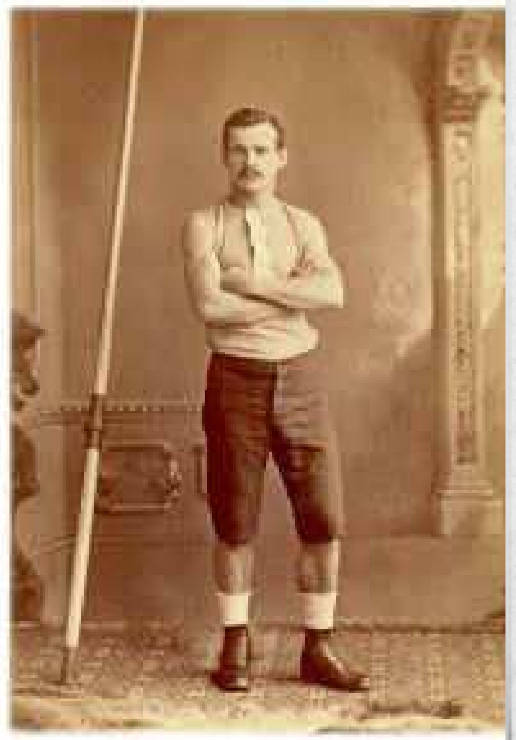
”Evolutionary Constraints”

- Race duration ~ 6-7 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



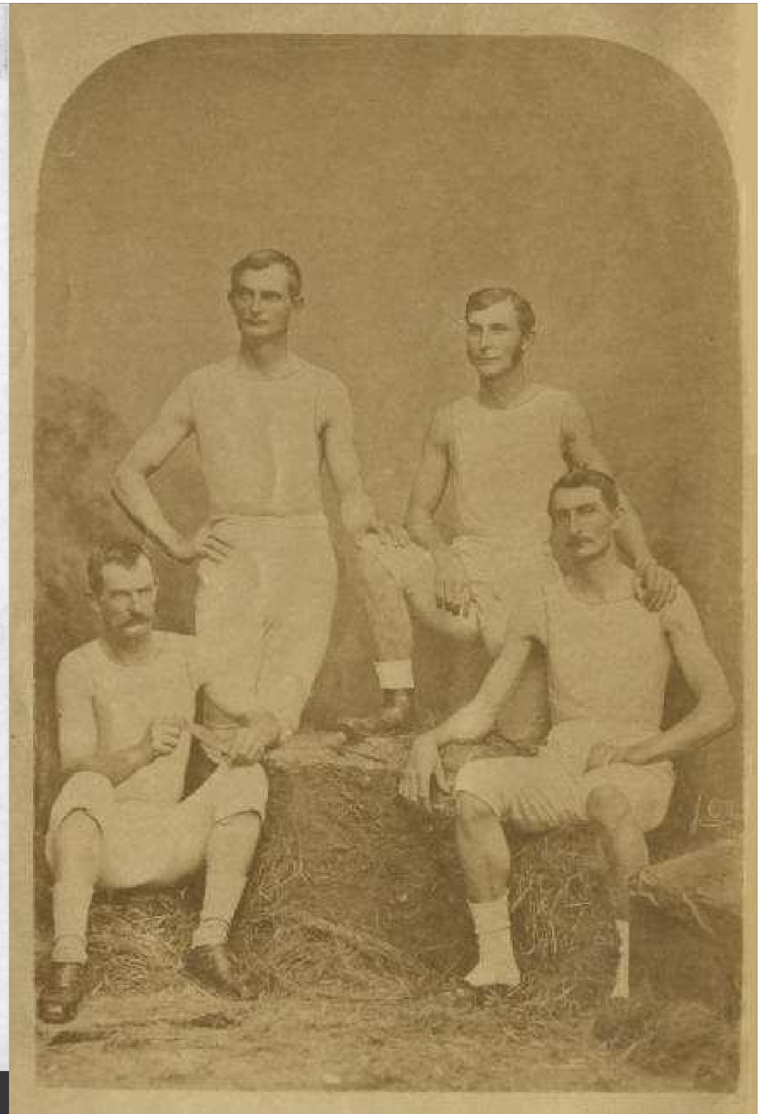
These constraints result in:

- 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?

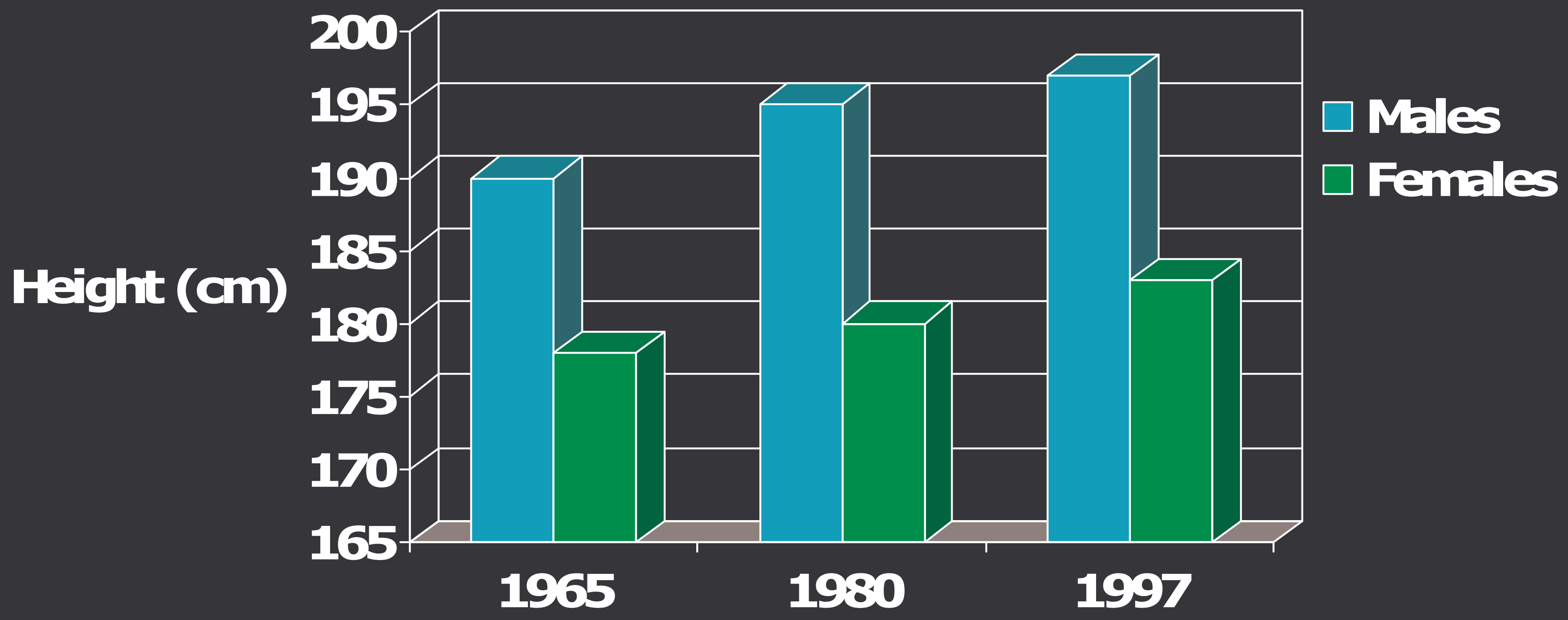


Ward Brothers ca 1865
185cm?
80+kg?

”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.

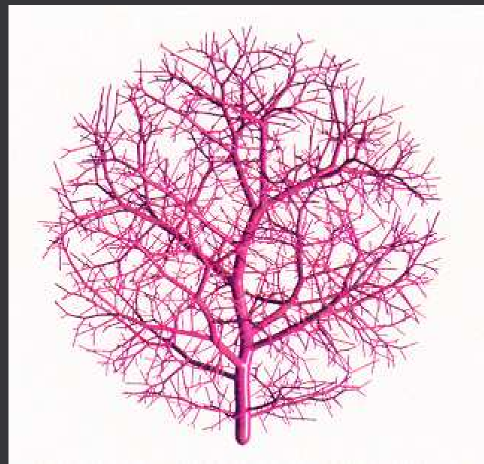
Taller Population= Taller Elite Rowers

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

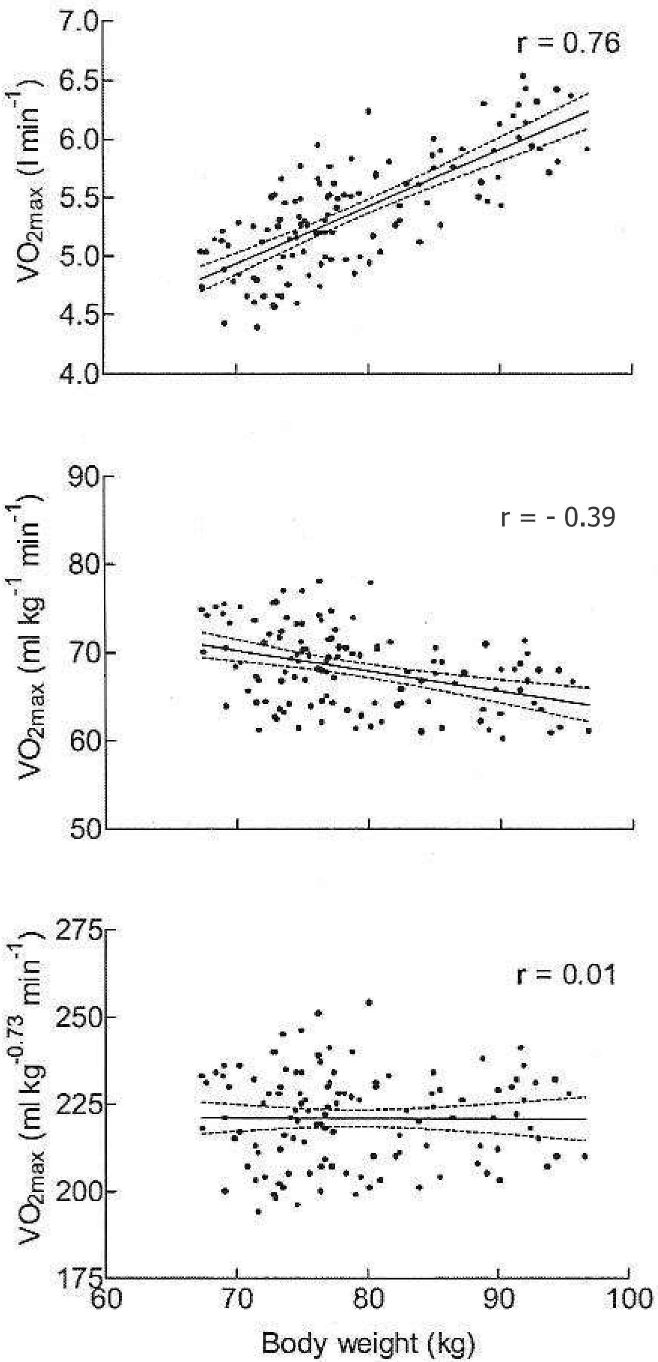
Scaling problems- Geometry or fractal filling volumes?

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.



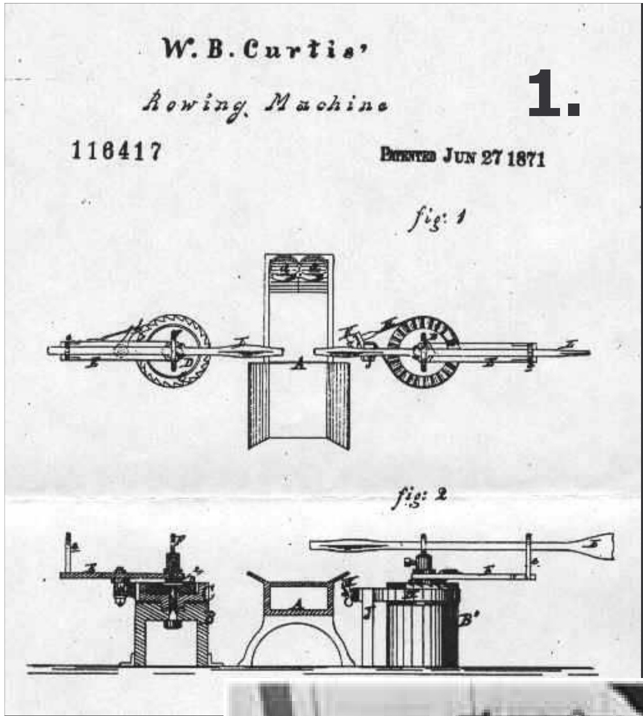
VO_2 body mass scaling in elite rowers

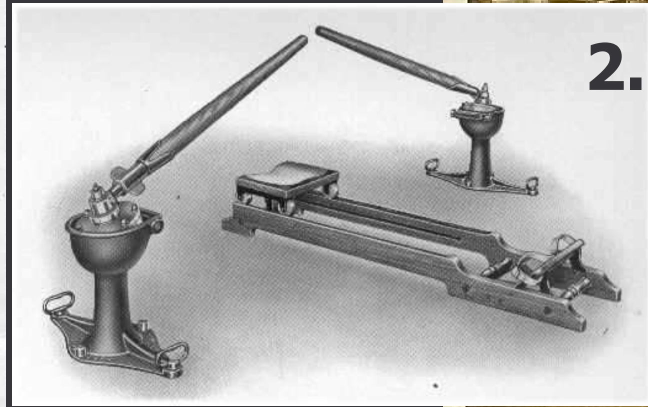
Relationship between maximal oxygen uptake and body mass for 117 Danish rowers
(national team candidates)

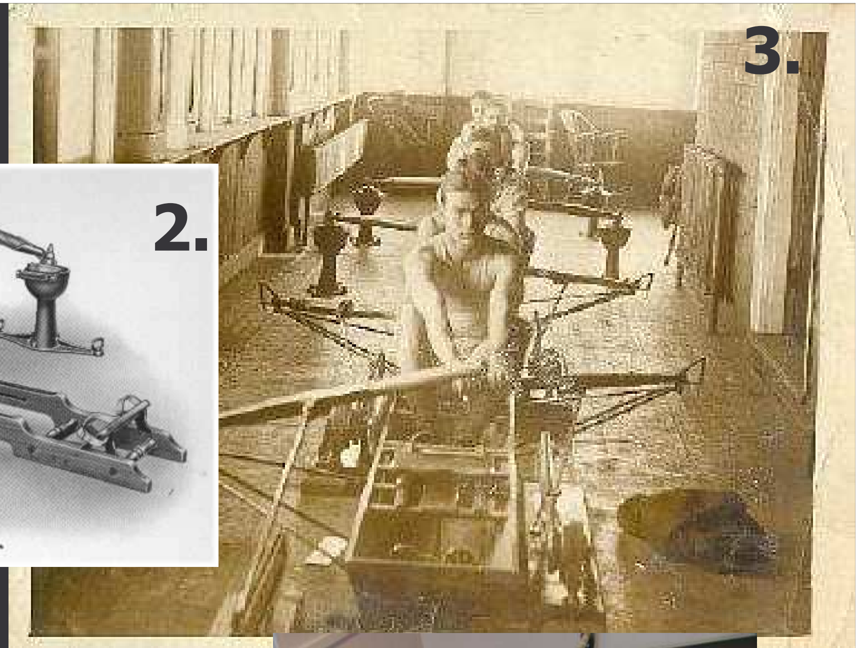
From: Jensen, K., Johansen, L, Secher, N.H. Influence of body mass on maximal oxygen uptake: effect of sample size. Eur. J. Appl. Physiol. 84: 201-205, 2001.

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

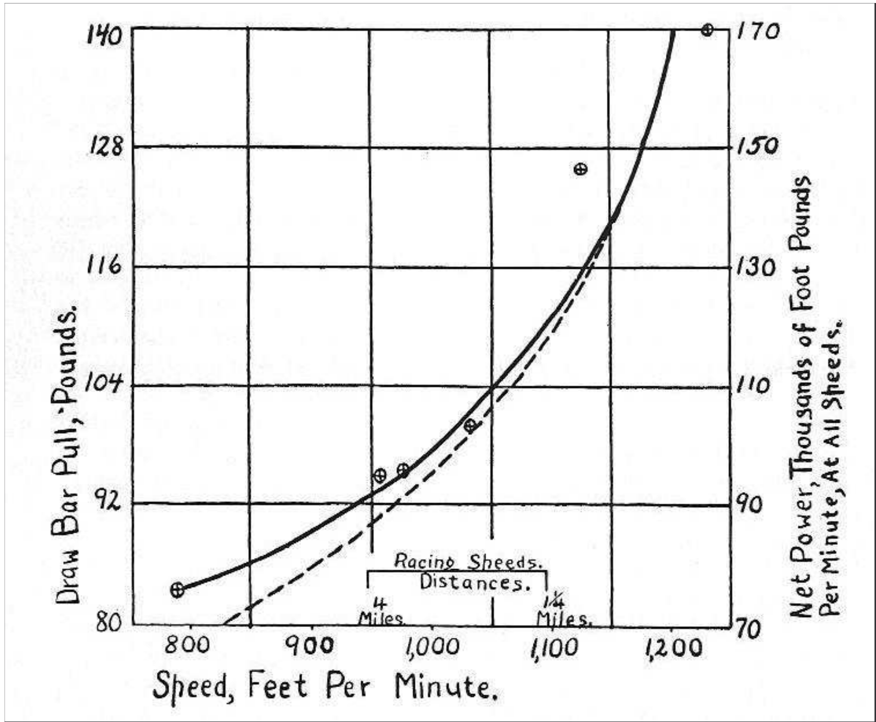
The Maximum of Human Power and its Fuel

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



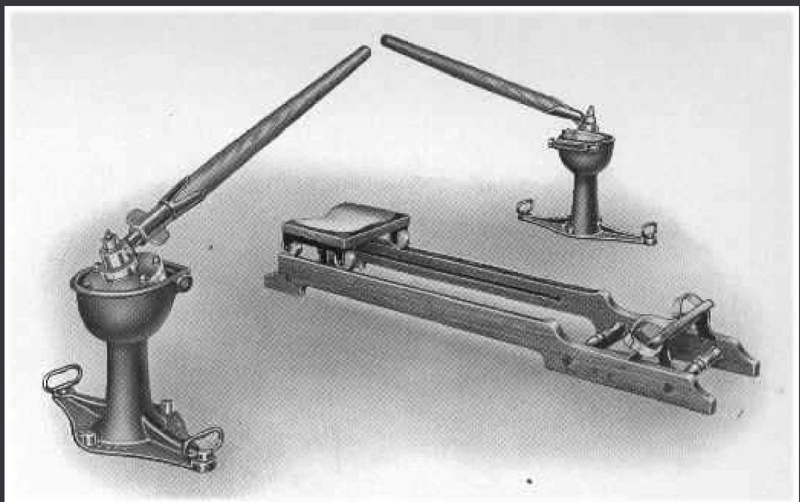
Estimated external work required at racing speed based on:

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

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

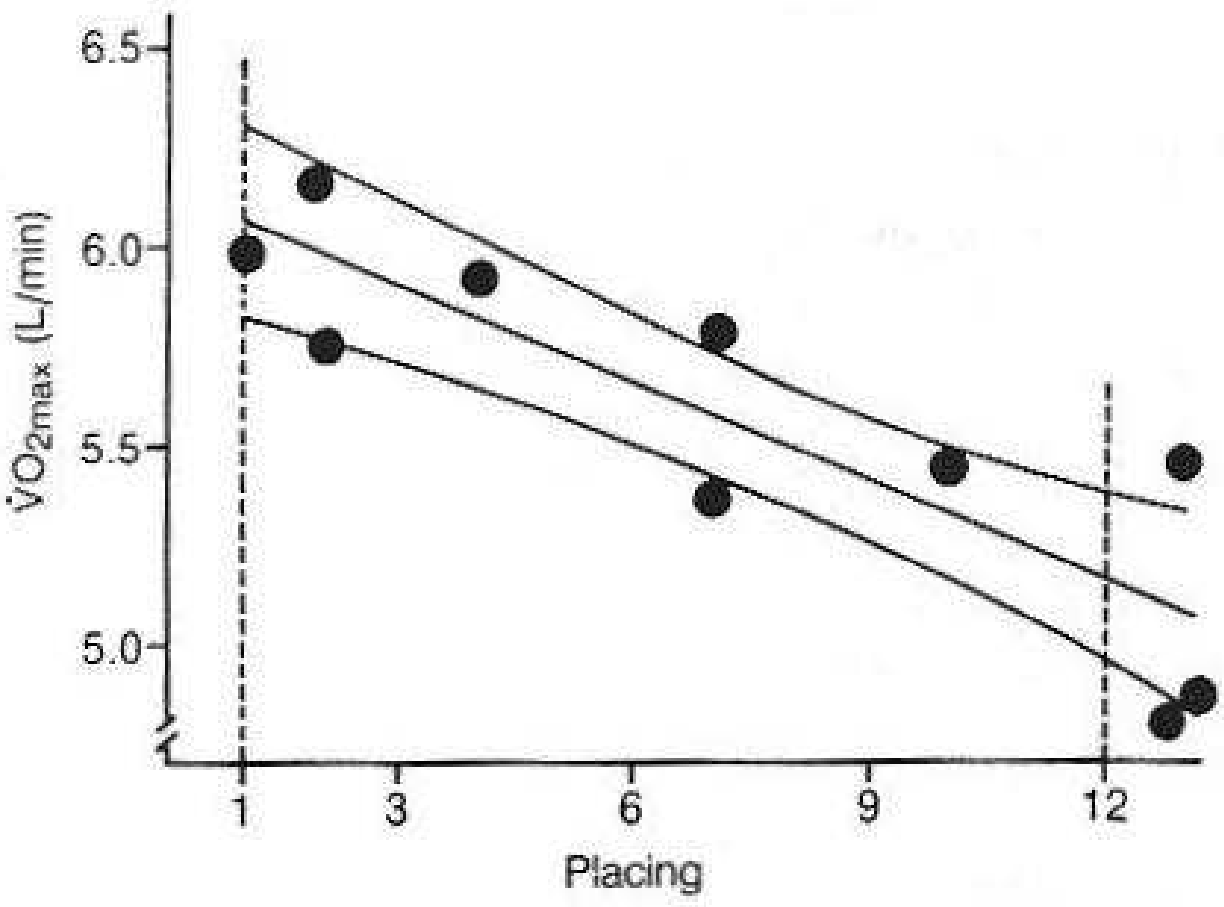
Equals ~ 6 Liter/min O_2 cost

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



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

1970s - VO_2 max vs boat placement in international regatta



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

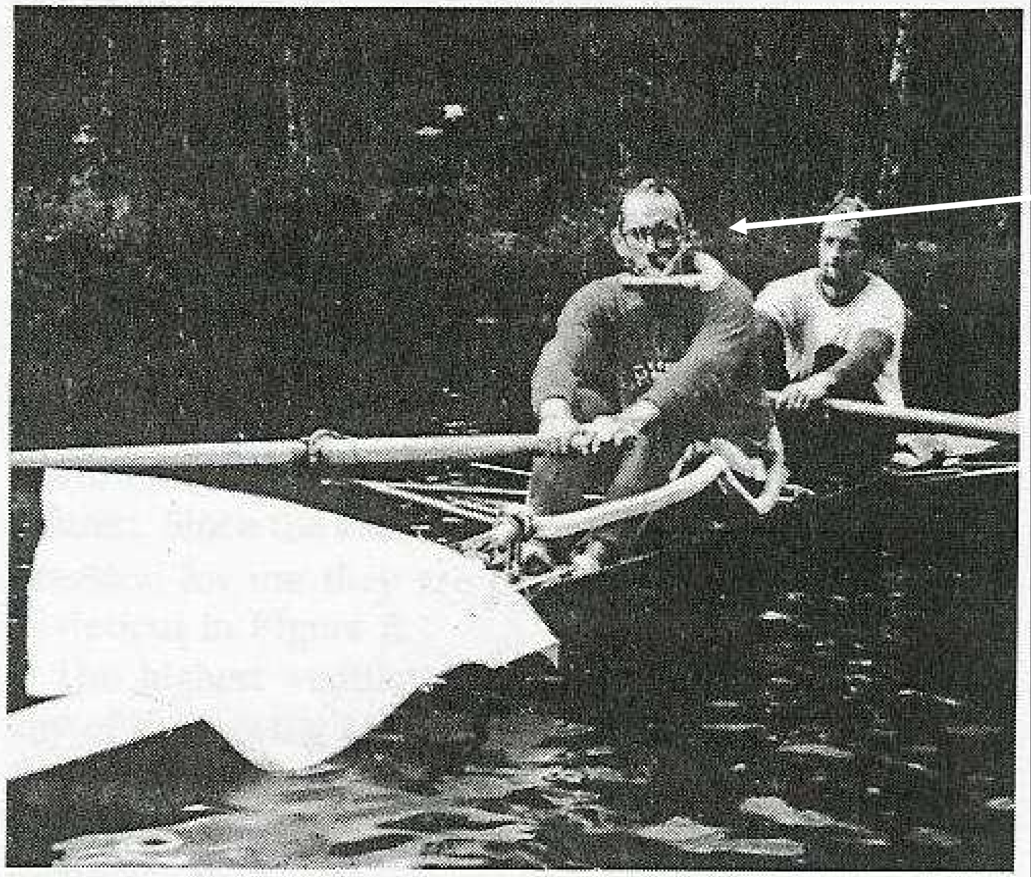
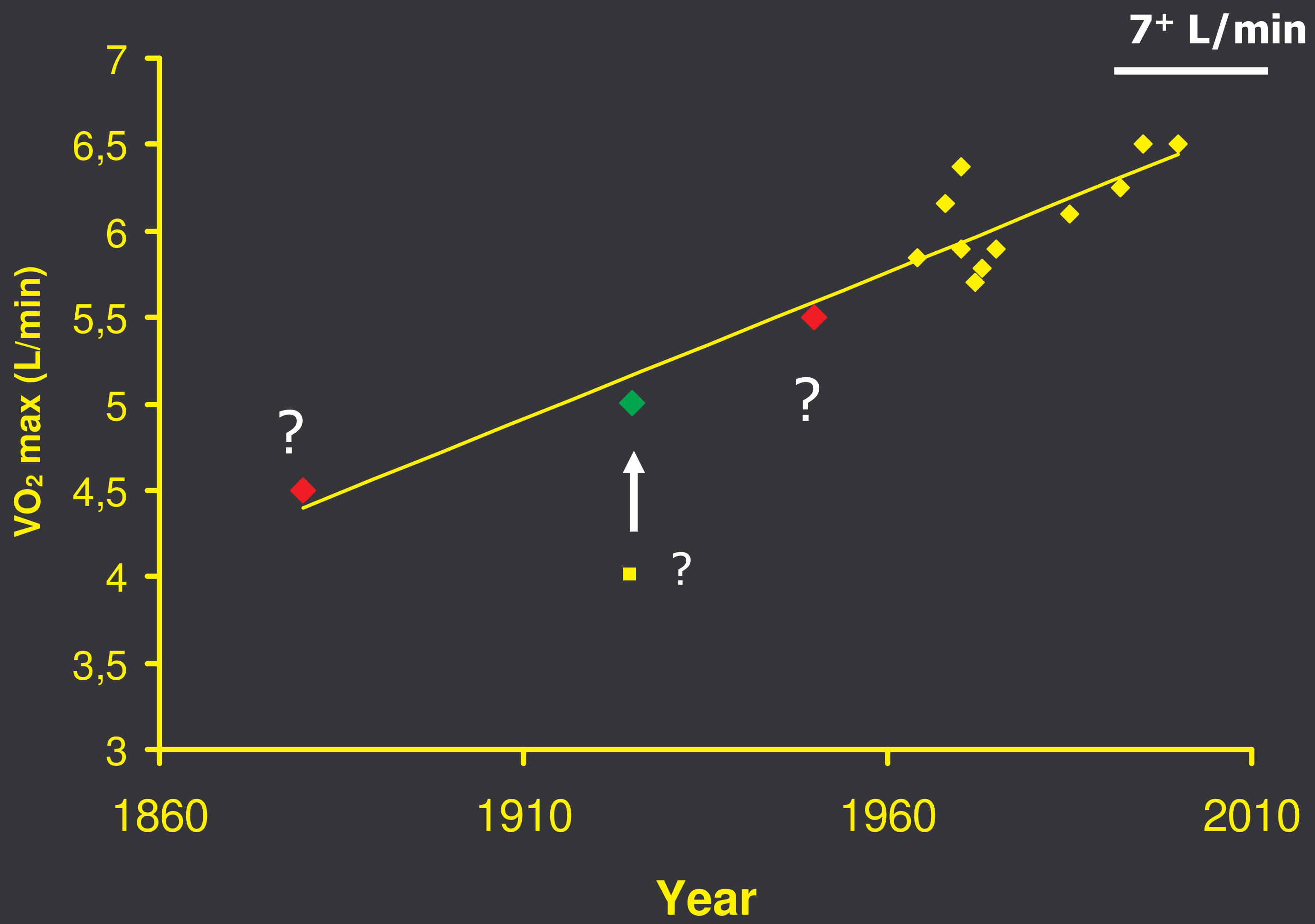


FIGURE 1–Gas collection apparatus in the coxless pair.

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.

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

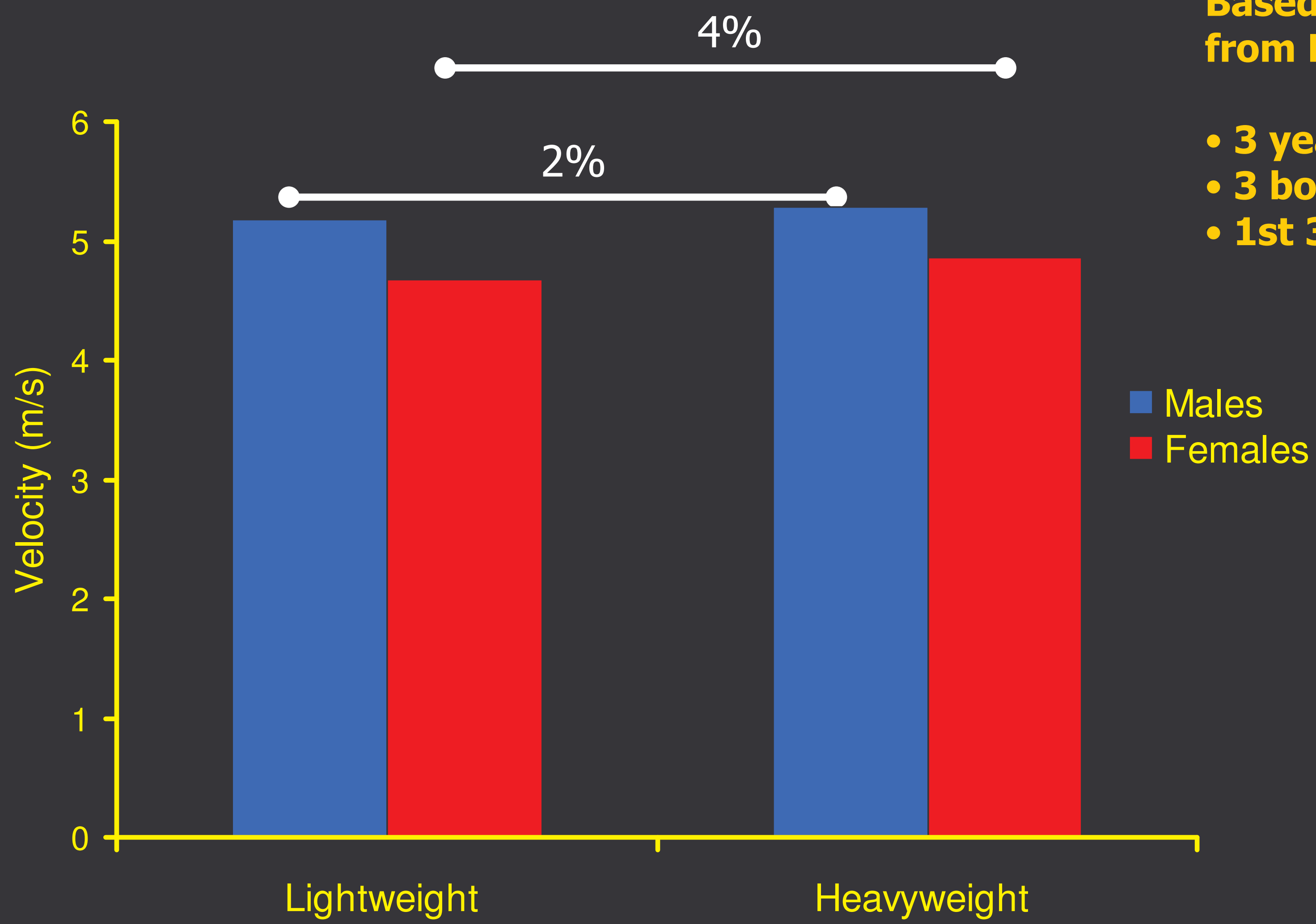
"Typical World Class"
XC skiers

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

Allometrically equivalent rower?

7.5 L/min, 95kg, (not measured)
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**

TRAINING,

IN

THEORY AND PRACTICE.

BY

ARCHIBALD MACLAREN.

London:

MACMILLAN AND CO.

186[?]

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. Beer, one pint.	
Bed at 10.0		

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.

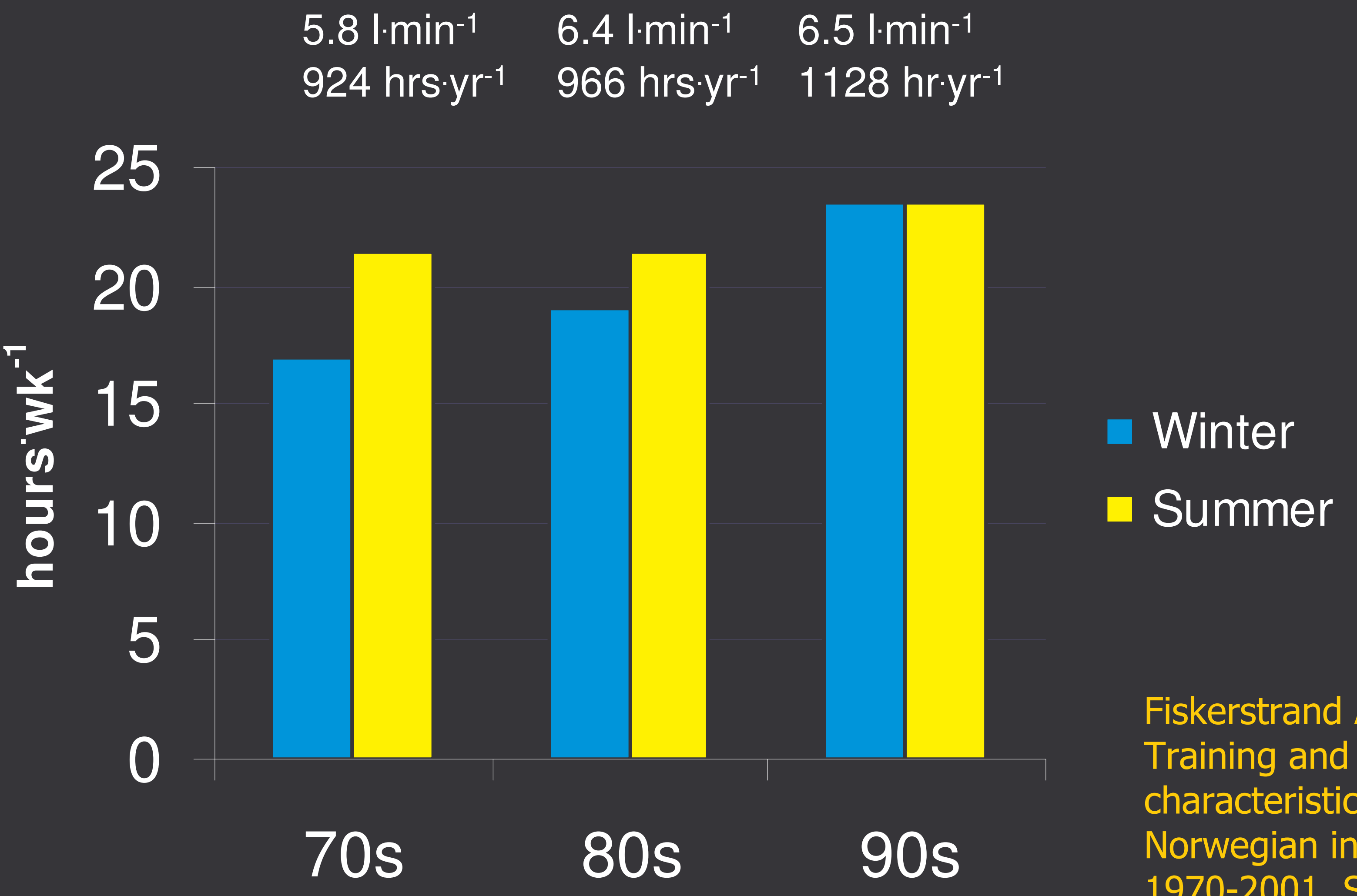
Mon	8:00	Weights	120 min	
	10:00	Row	70 min Steady state in pairs	HR 144-148
	4:00	Row	100 min Steady state in pairs	HR 140-144
Tues	8:00	Row	2 x 5x5 min ON/1 min OFF in pairs	HR 180-185
	10:30	Erg	12 kilometers	HR 150
	4:00	Row	100min Steady state in eight	
Wed	8:00	Weights	120 min	
	10:00	Run	3 x 10 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

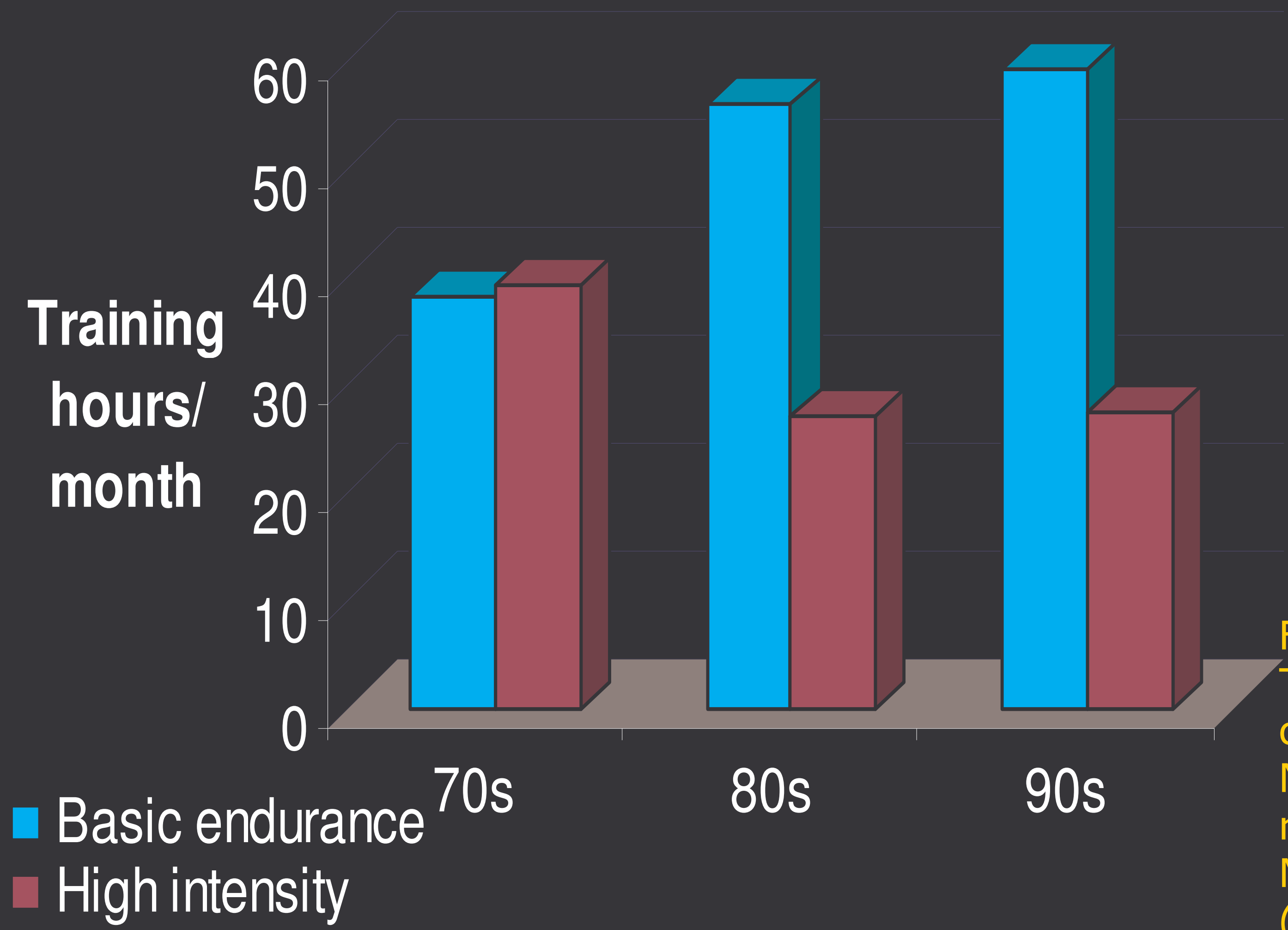
From US Women's national team 1996

Developments in training over last 3 decades



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



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.

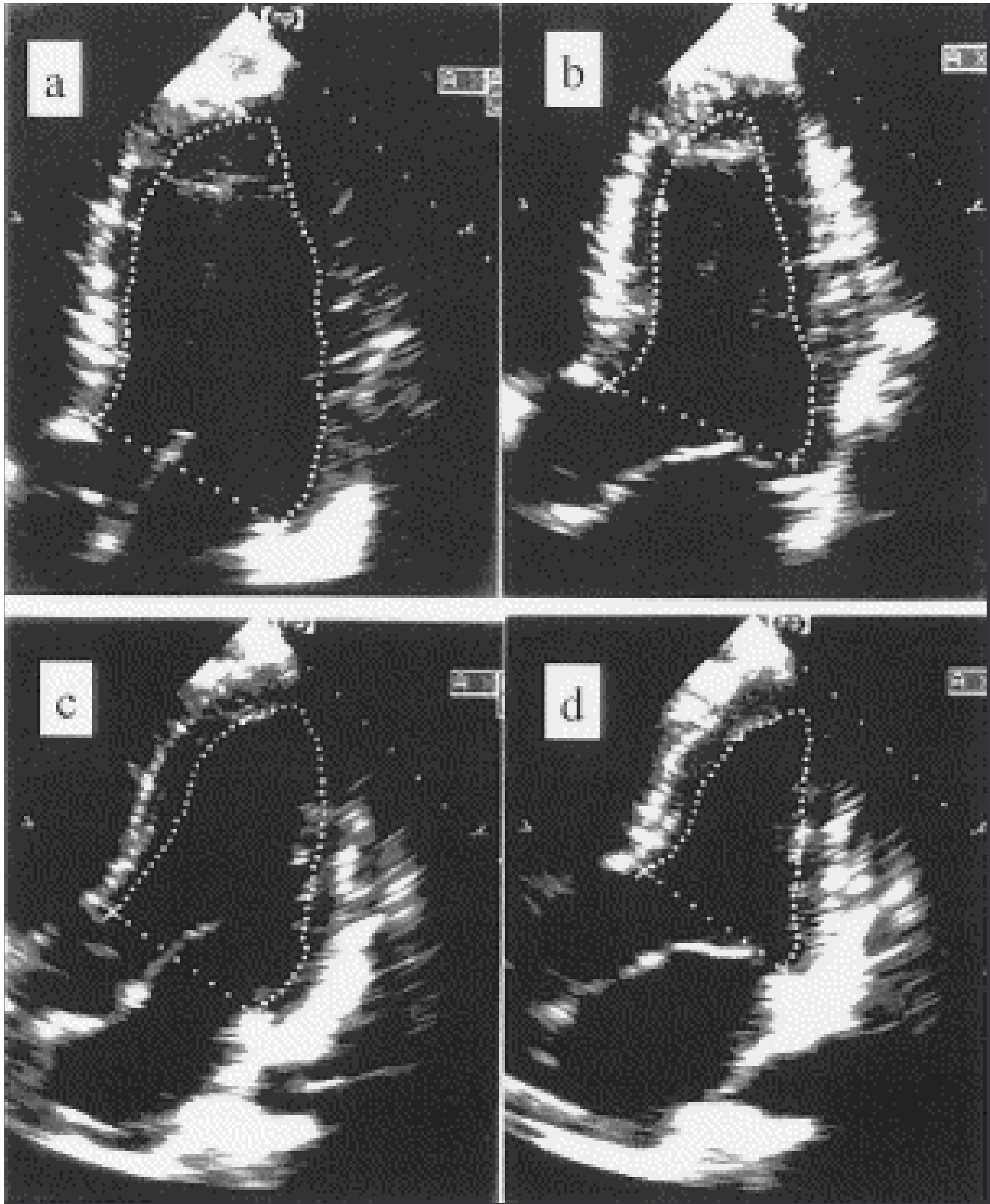
See also: Thompson P.D. Historical aspects of the Athletes Heart. MSSE 35(2), 364-370 2003.

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.

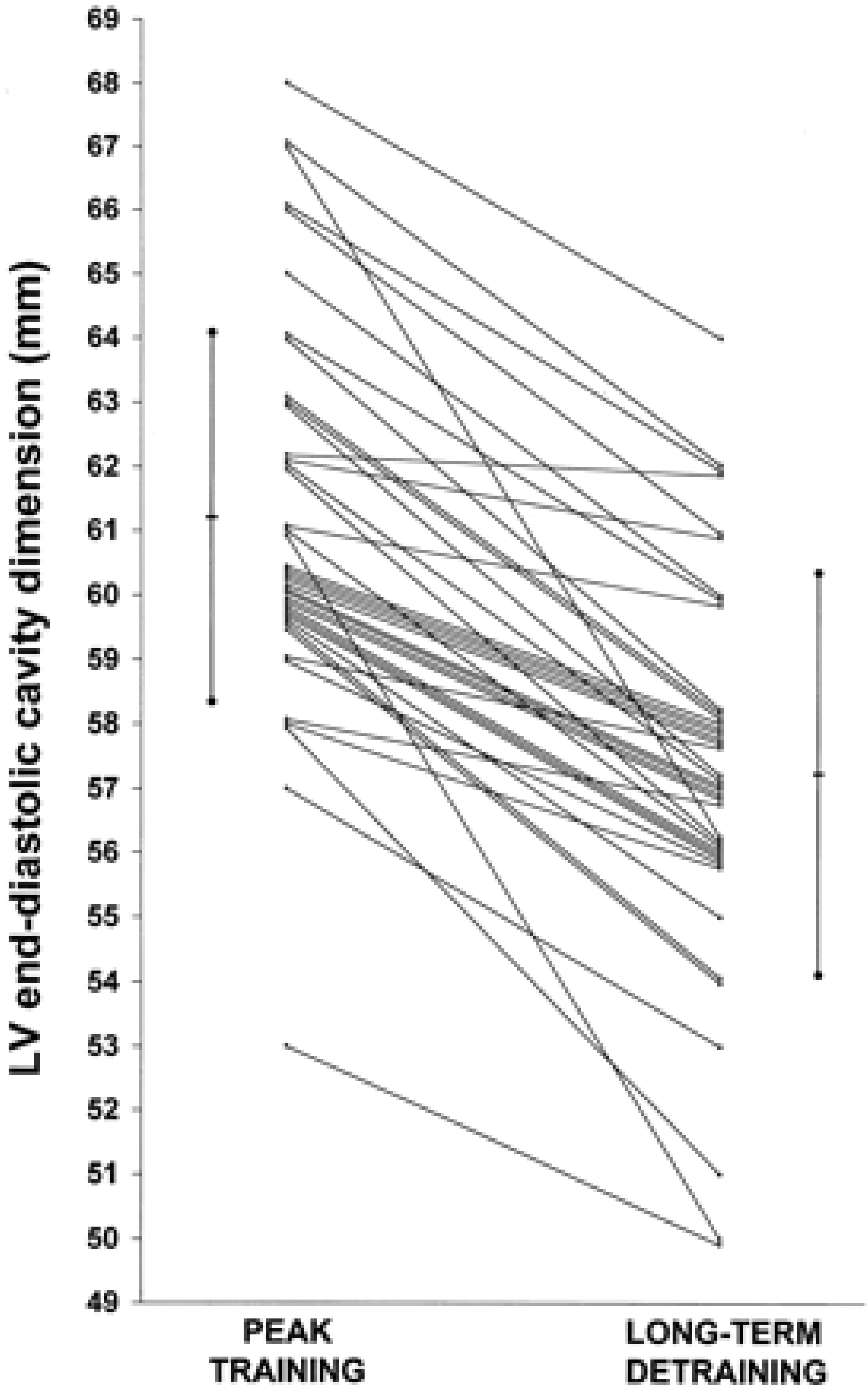
from: Pelliccia A. et al. The upper limit of physiologic cardiac hypertrophy in highly trained elite athletes. New England J. Med. 324, 295-301, 1991.



elite rower

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 guage 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

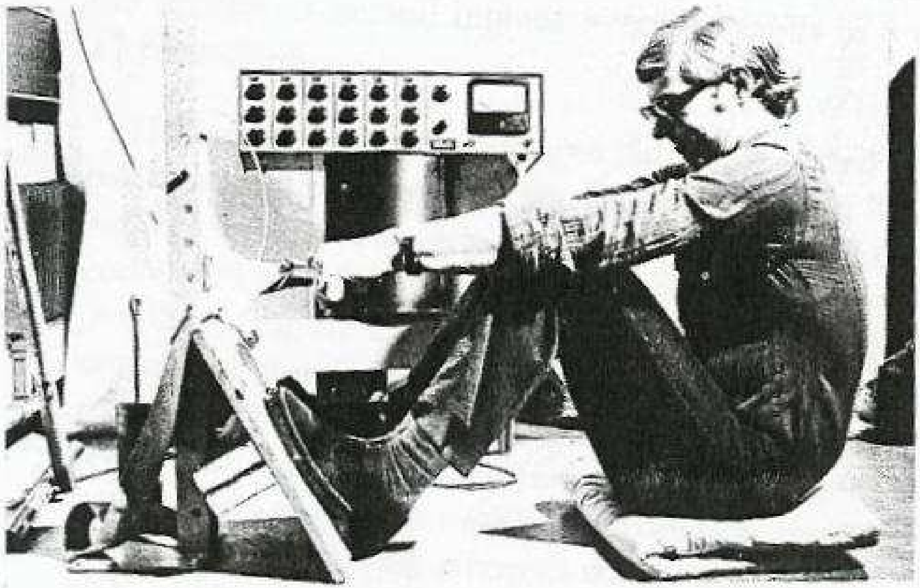


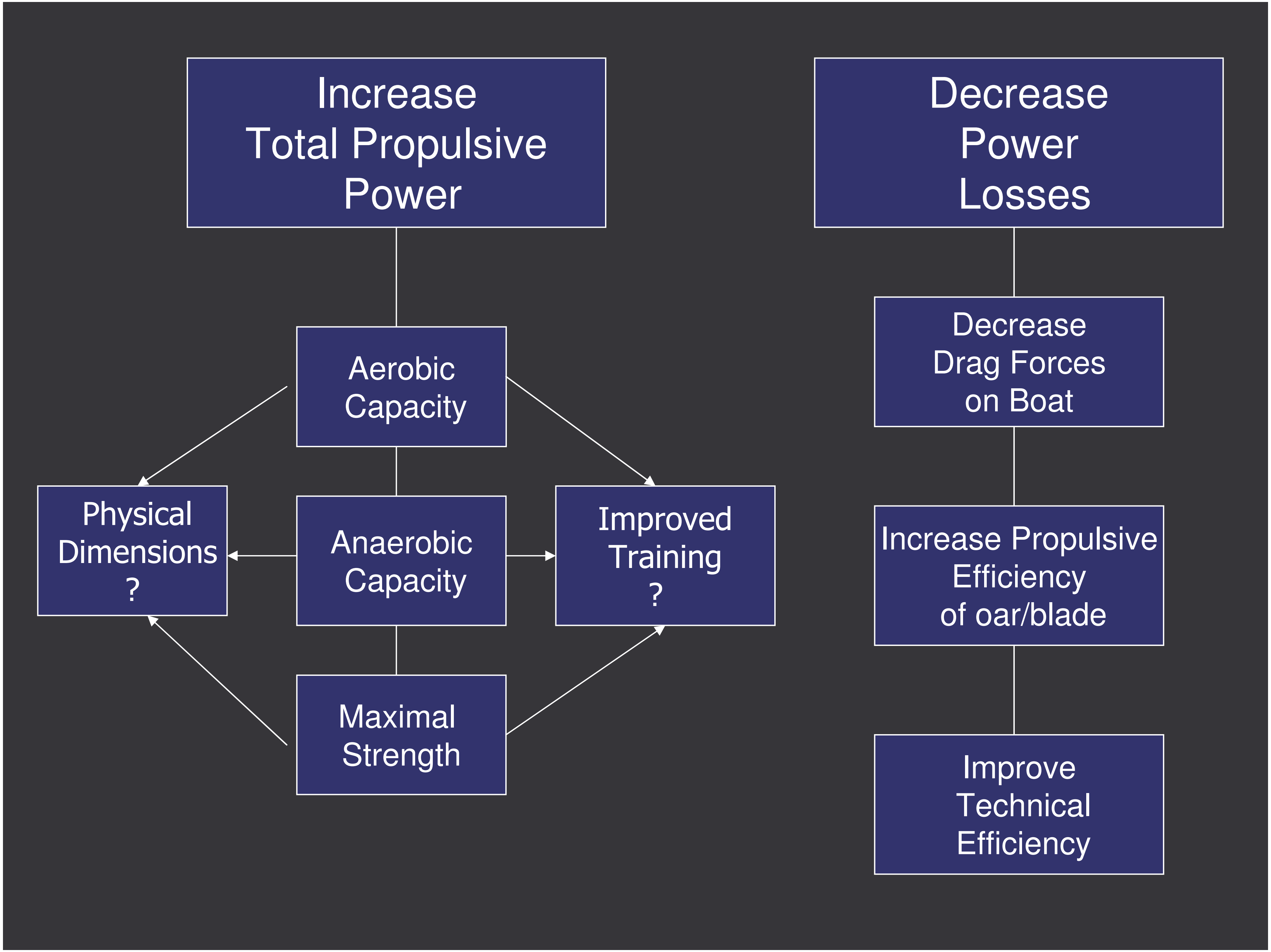
Figure 1—Apparatus and set-up for determination of rowing strength.

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

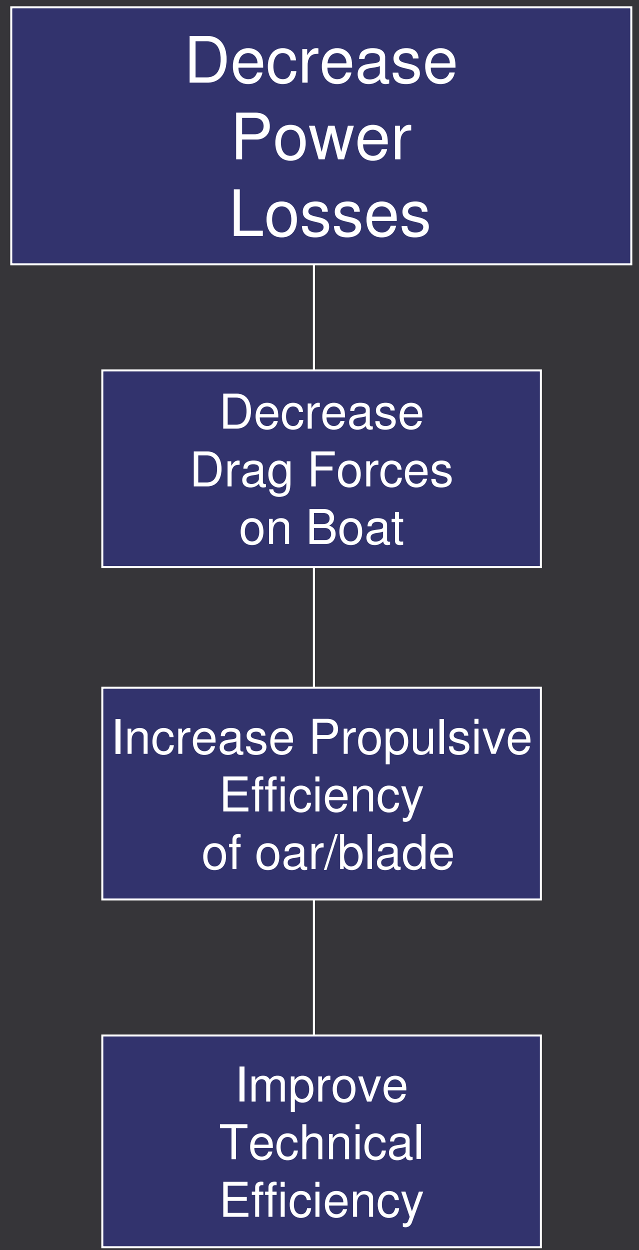
Measured isometric force in 7 Olympic/world medalists, plus other rowers and non-rowers

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

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



Increase Total Propulsive Power
Aerobic Capacity
Physical Dimensions ?
Anaerobic Capacity
Improved Training ?
Maximal Strength
Decrease Power Losses
Decrease Drag Forces on Boat
Increase Propulsive Efficiency of oar/blade
Improve Technical Efficiency


Decrease Power Losses
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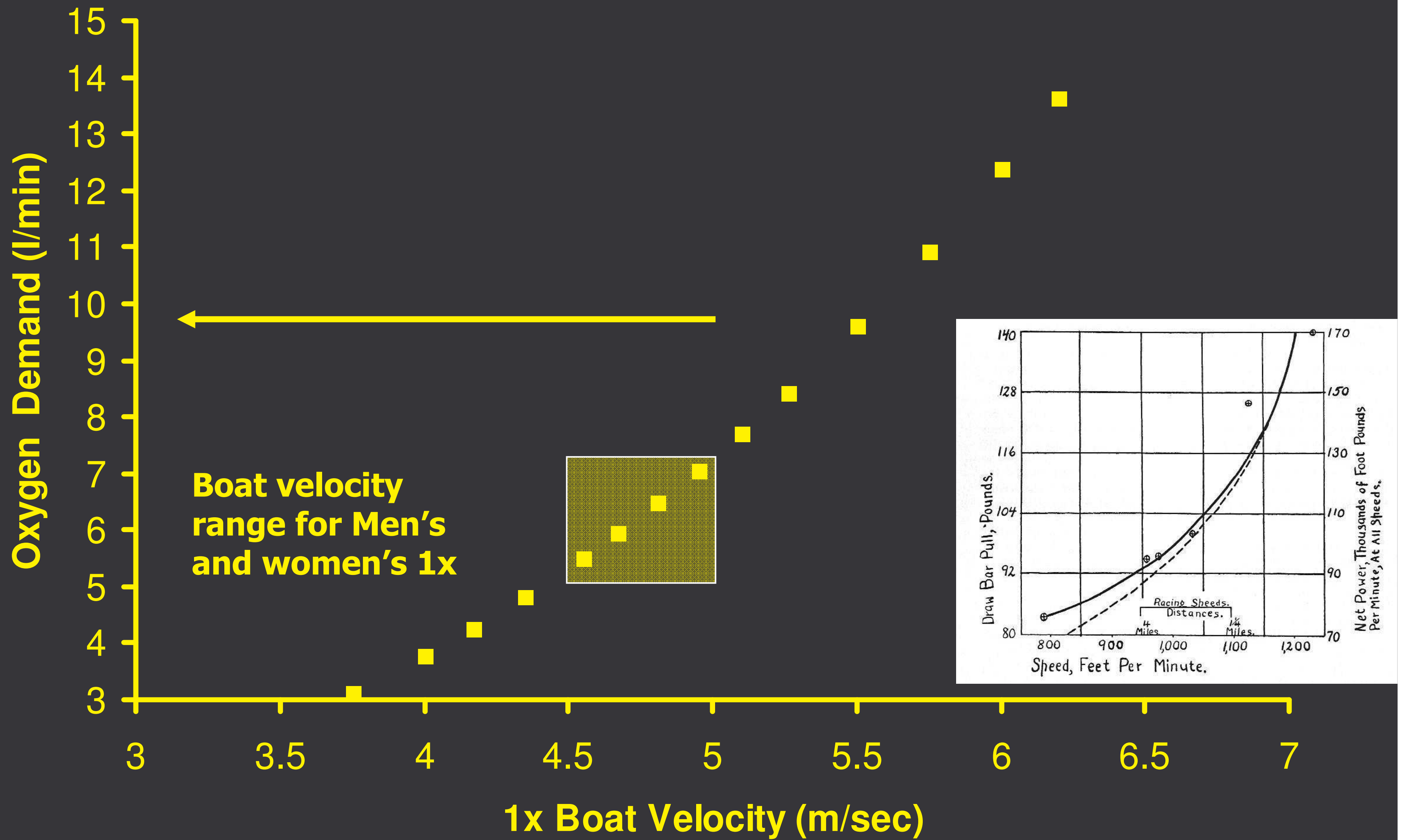
Boat Velocity – Oxygen Demand Relationship

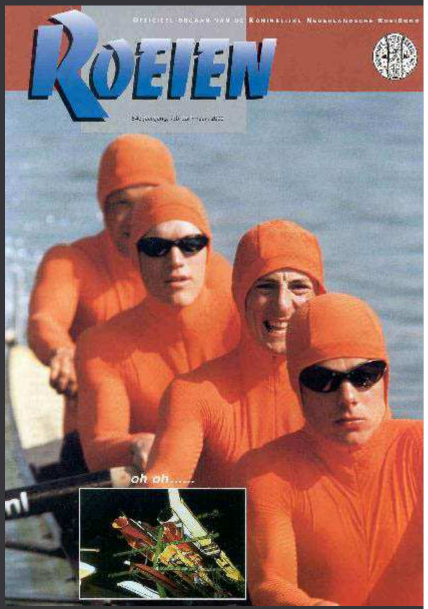


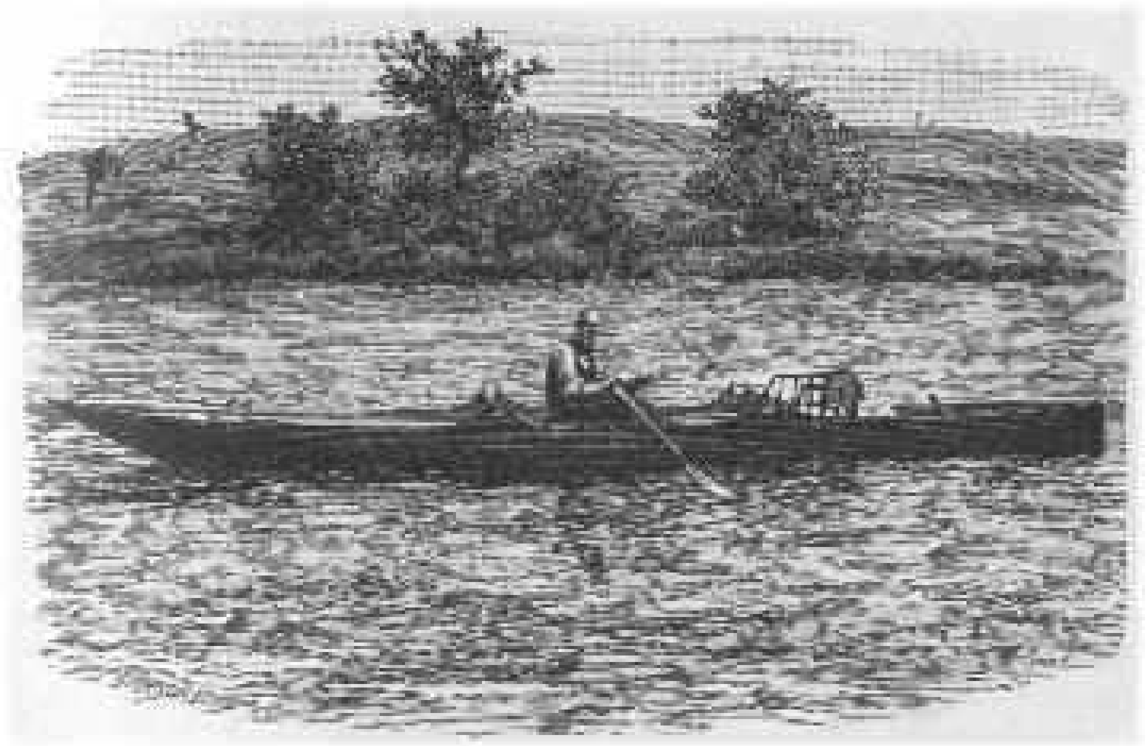
Drag Forces on the Boat and Rower

- Skin (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

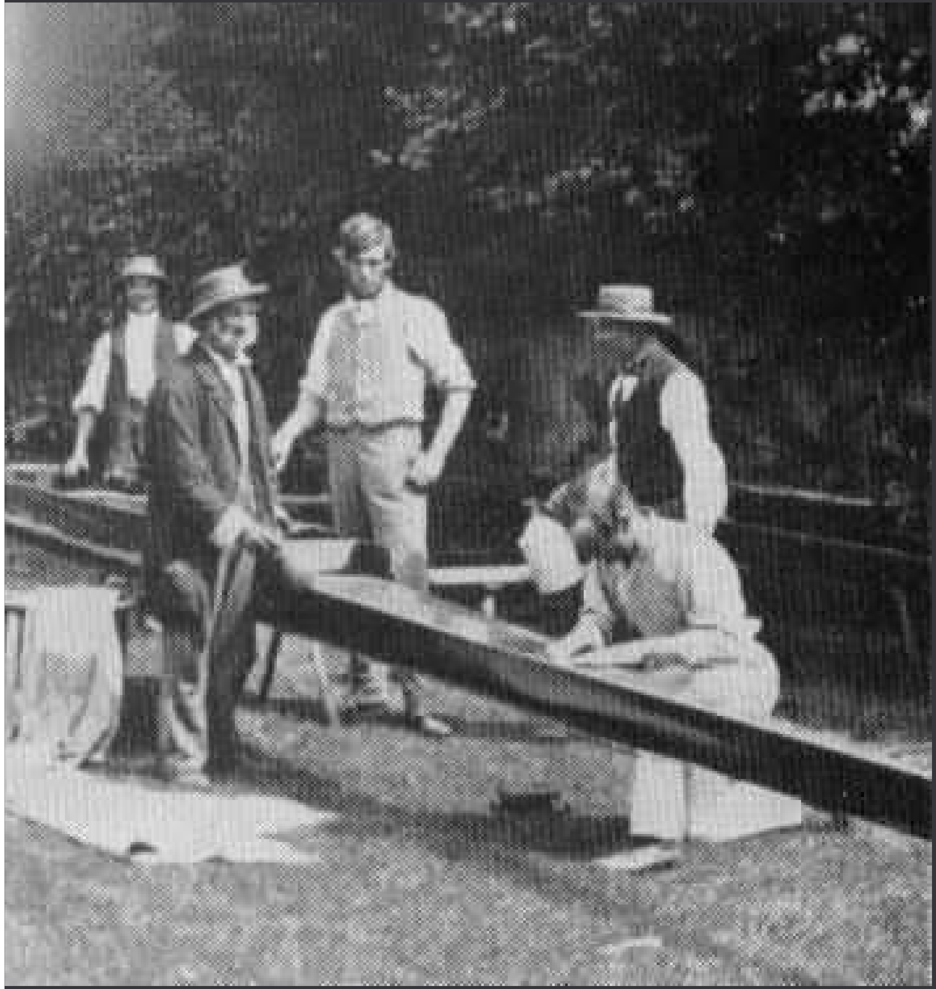




In-rigged wherry typical of those used in racing prior to 1830

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

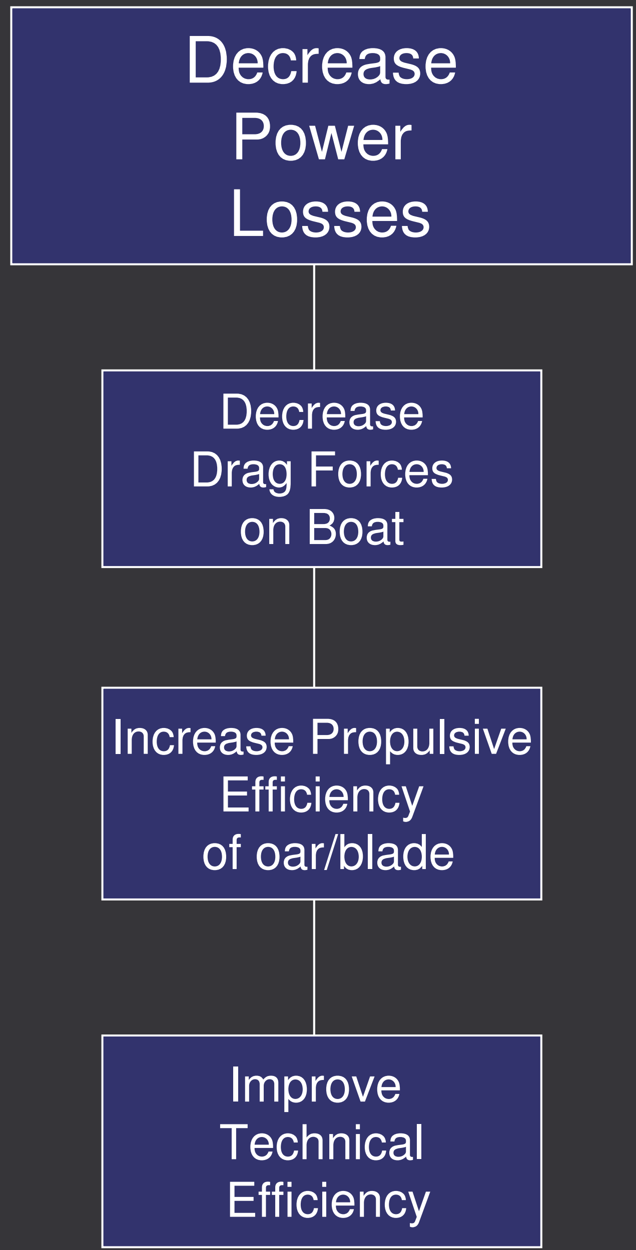
$$\Delta V/V = -(1/6)\ \Delta\ M/M_{total}$$

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

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!

Flyak hydrofoil video


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

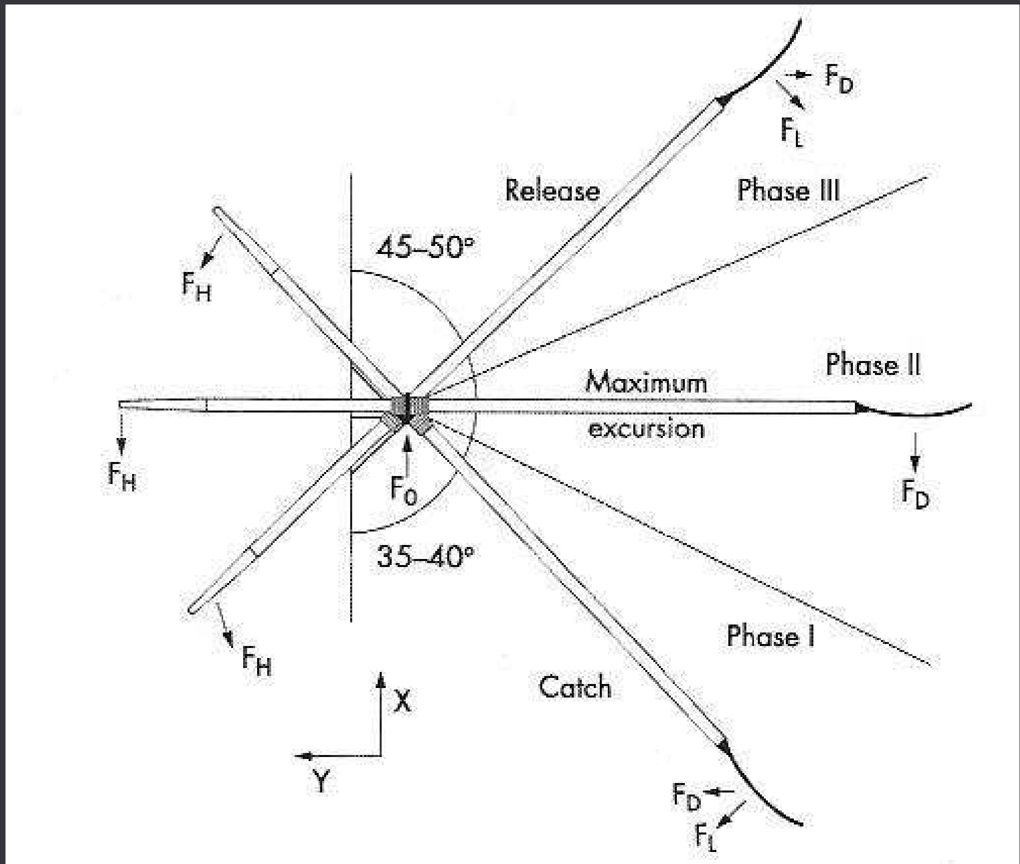
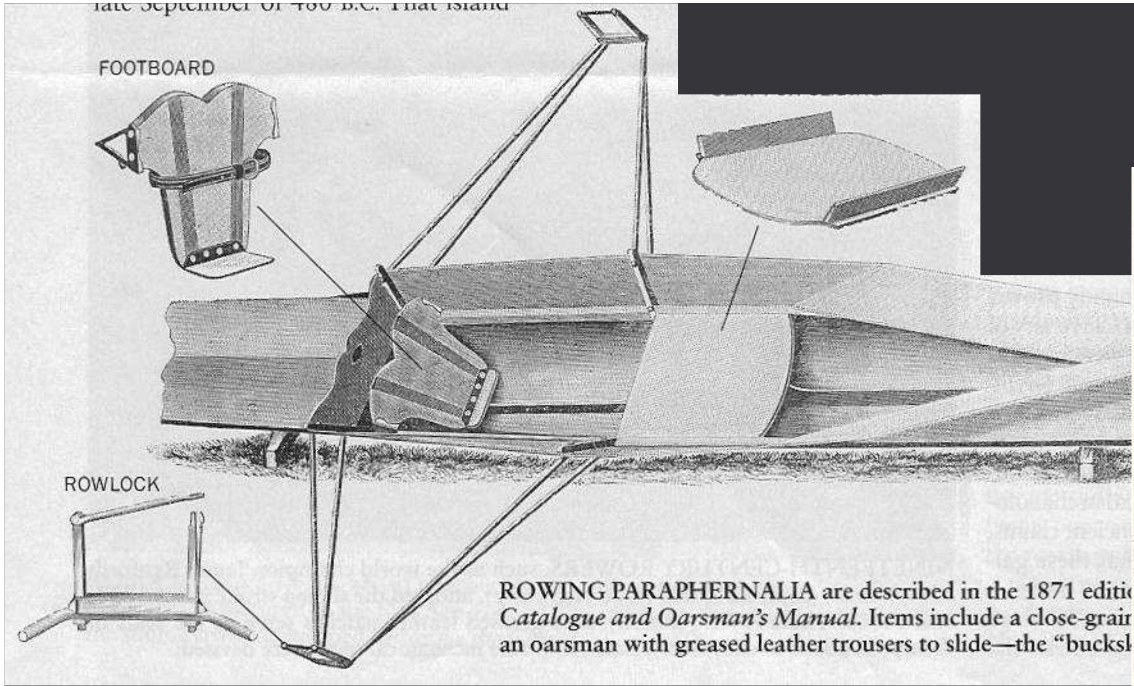
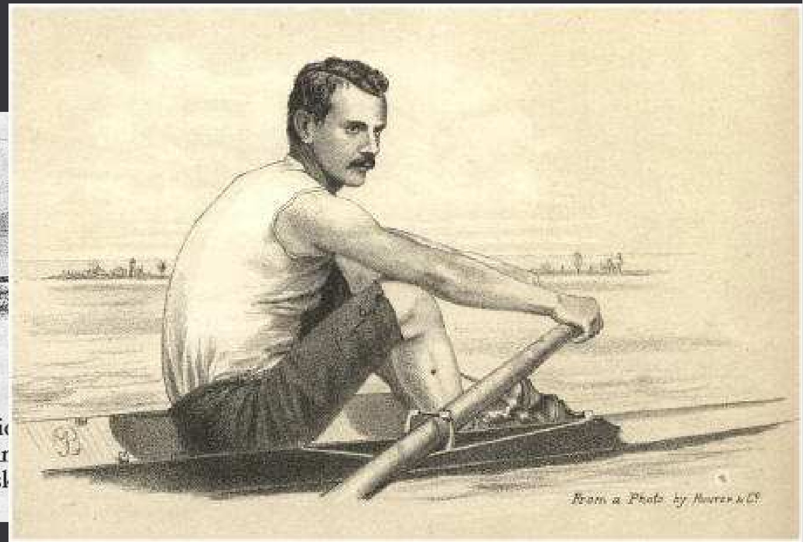
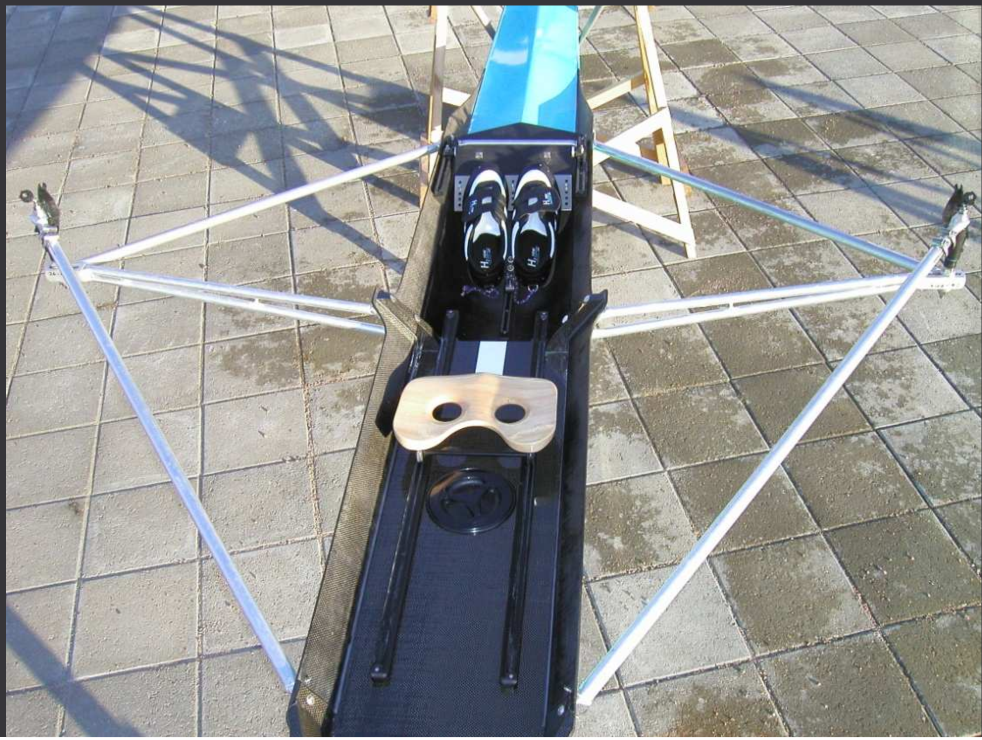


Figure from:

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


late September of 480 B.C. That island
FOOTBOARD
ROWLOCK
ROWING PARAPHERNALIA are described in the 1871 editic
Catalogue and Oarsman's Manual. Items include a close-grair
an oarsman with greased leather trousers to slide—the "bucksl


From a Photo. by Hunter & Co.

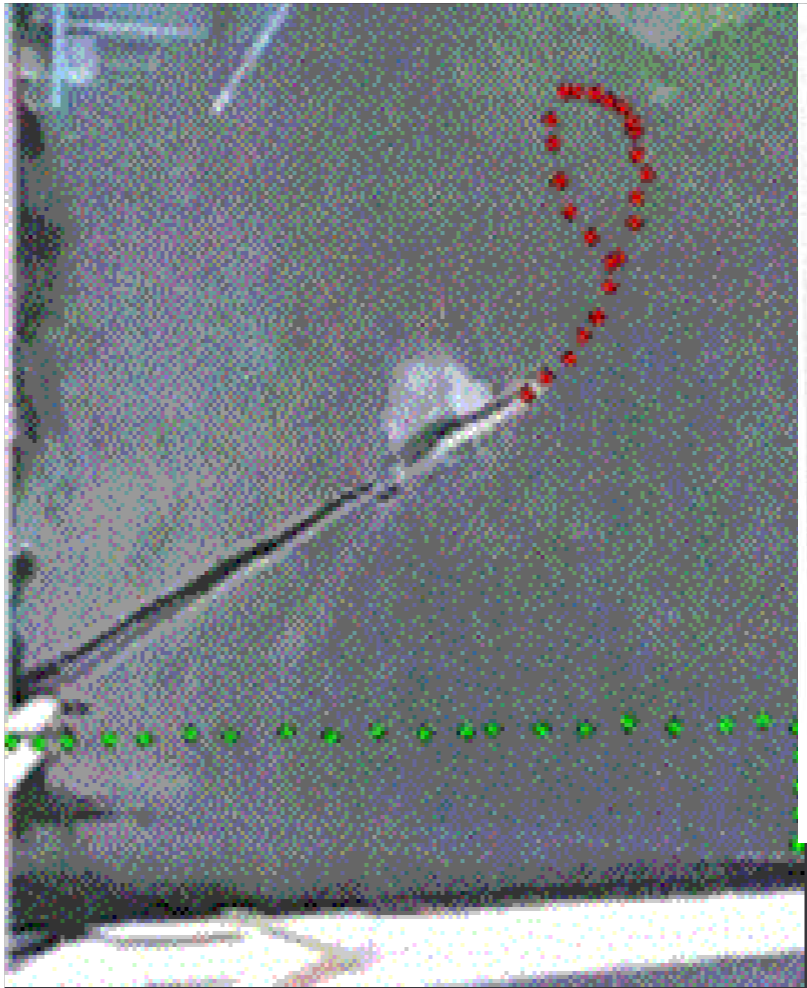


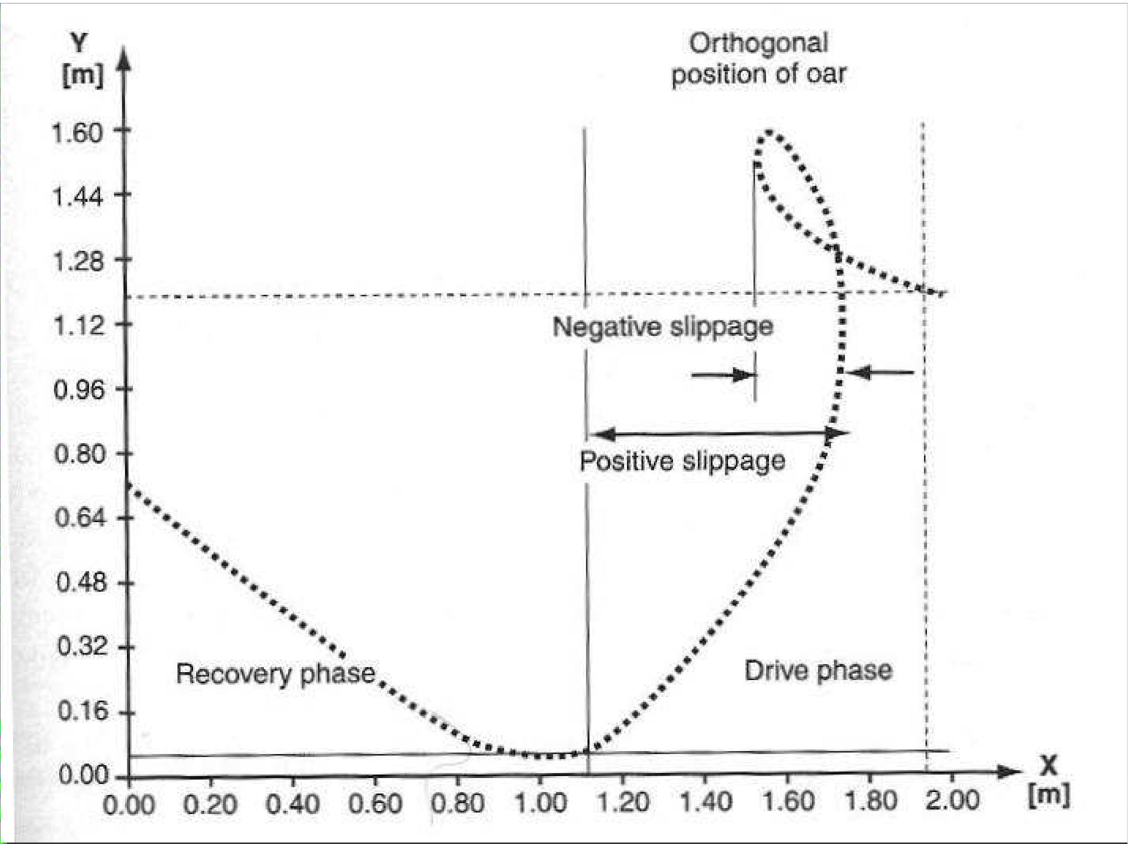

CROKER

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

Photo from www.concept2.com

Oar hydrodynamic efficiency- propelling the boat but not the water

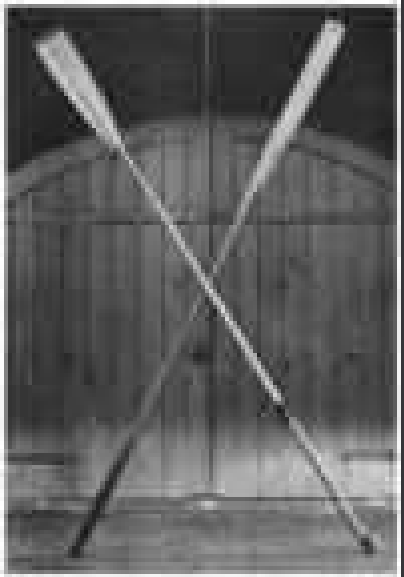
$$E_{hydro} = \frac{\text{Power applied}_{\text{rower}} - \text{Power loss}_{\text{moving water}}}{\text{Power applied}_{\text{rower}}}$$

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

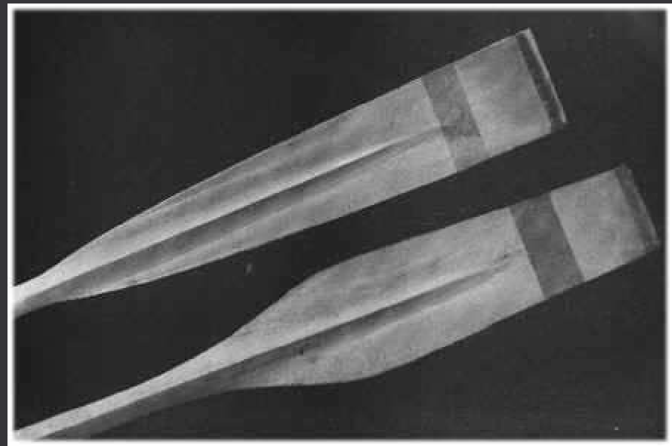
Oar power loss = blade drag force * *blade velocity (<u>slip</u>)*

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

Oar Evolution

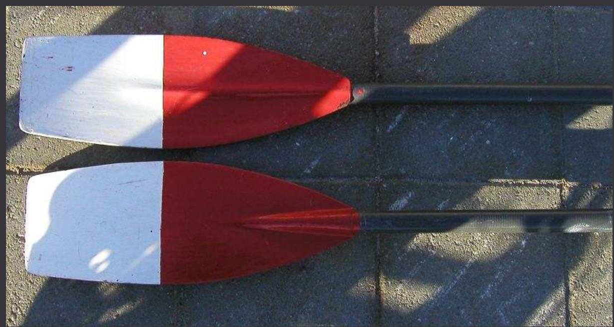


Square loomed scull 1847

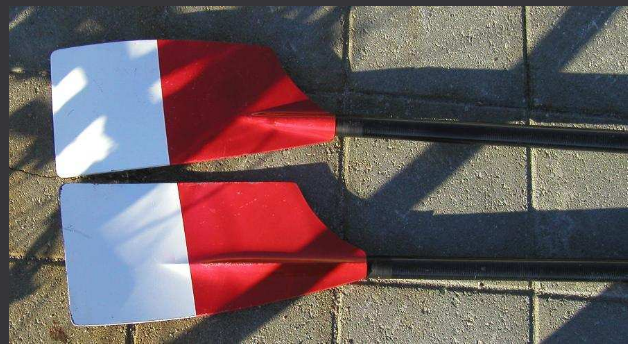


"Square" and "Coffin" blades 1906

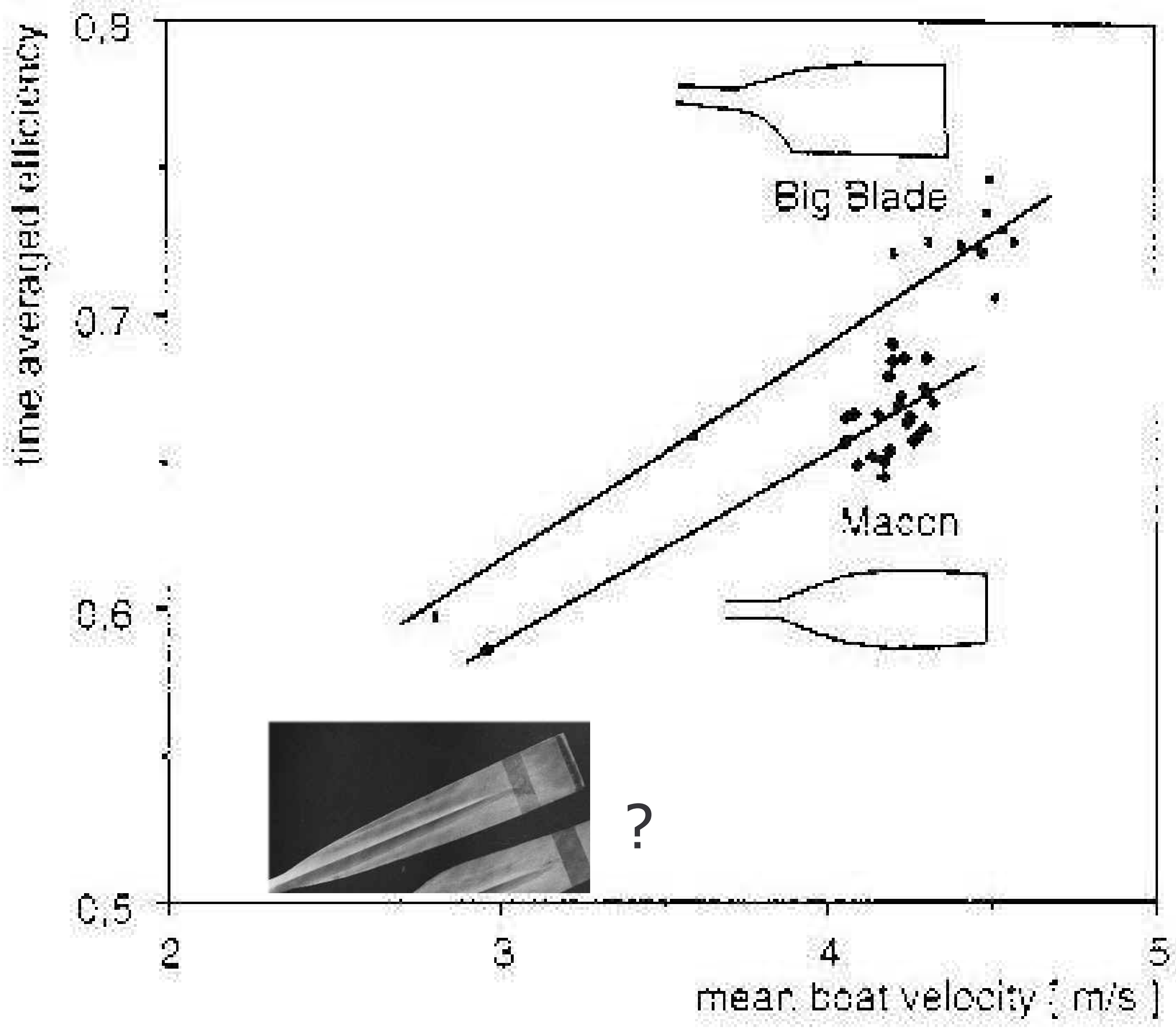
Macon blade-wooden shaft 1960-1977



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

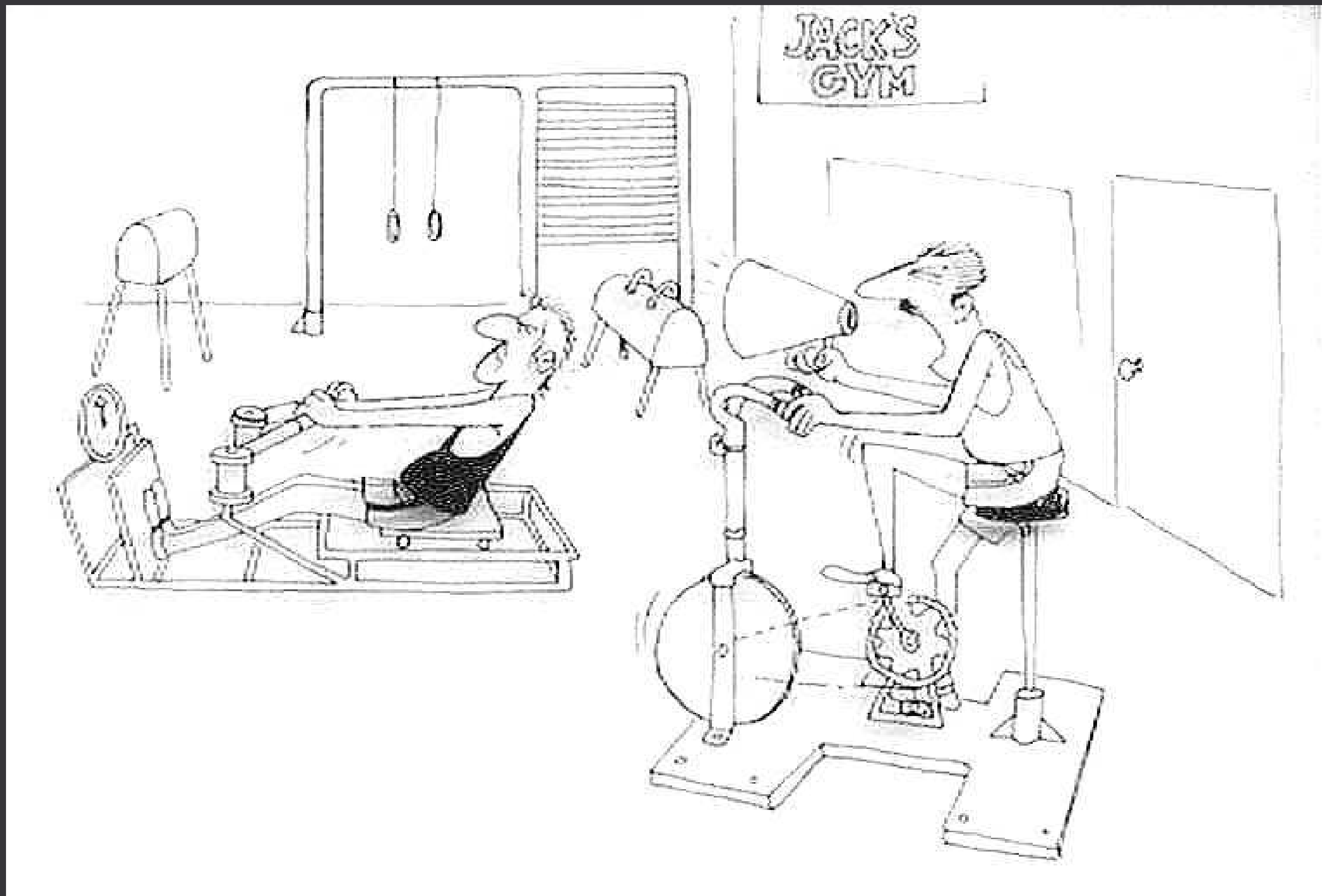
All pictures from www.concept2.com in exchange for unsolicited and indirect endorsement!

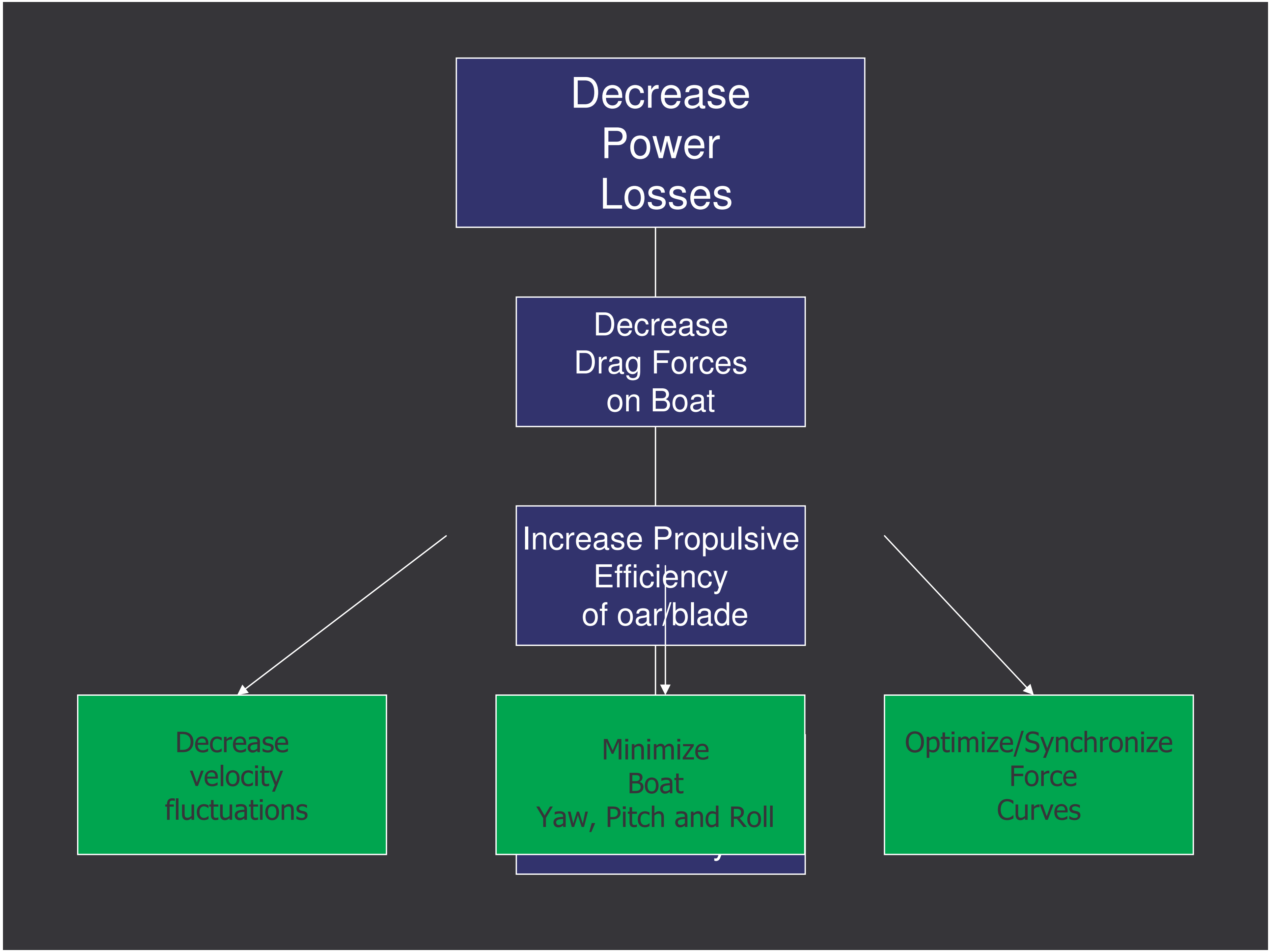
Effect of Improved Oars on boat speed?

- Kleshnev (2002) used instrumented boats and measurement of 21 crews to estimate an 18% energy loss to moving water by blade

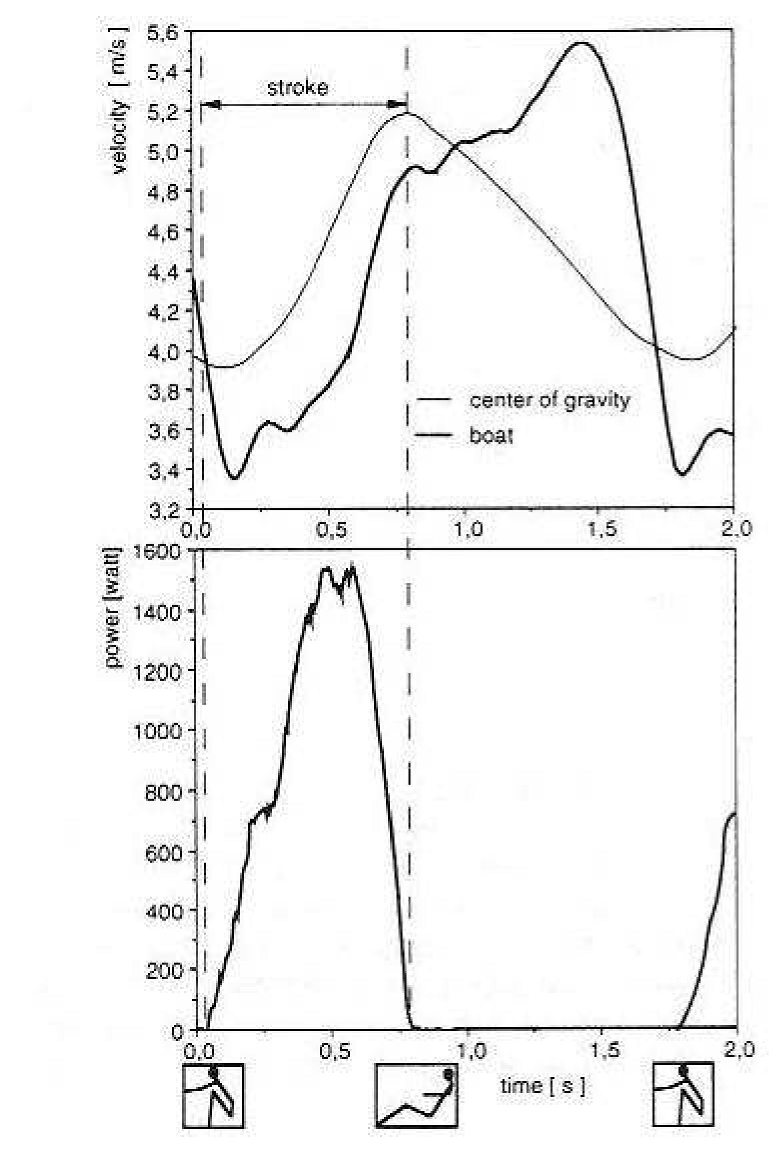
- Data suggests 2-3% gain in boat velocity possible with further optimization of oar efficiency (30-50% of the present ~ 6 % velocity loss to oar blade energy waste)

Rowing Technique: ”Ergs don’t float”




Decrease Power Losses
Decrease Drag Forces on Boat
Increase Propulsive Efficiency of oar/blade
Decrease velocity fluctuations
Minimize Boat Yaw, Pitch and Roll
Optimize/Synchronize Force Curves

Decreasing Velocity Fluctuations



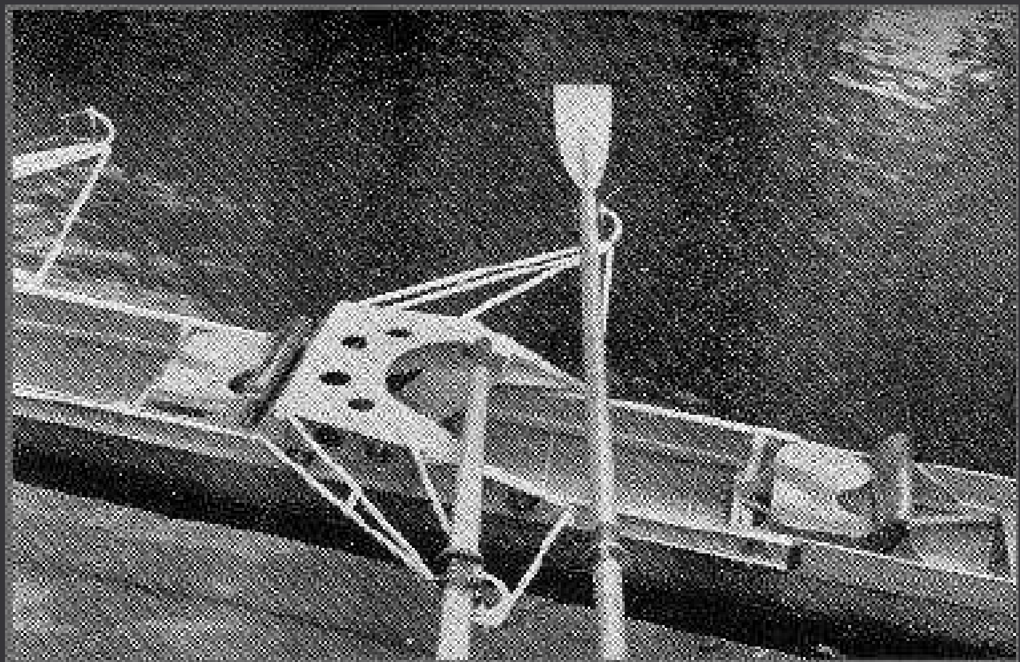
Sources

- 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)

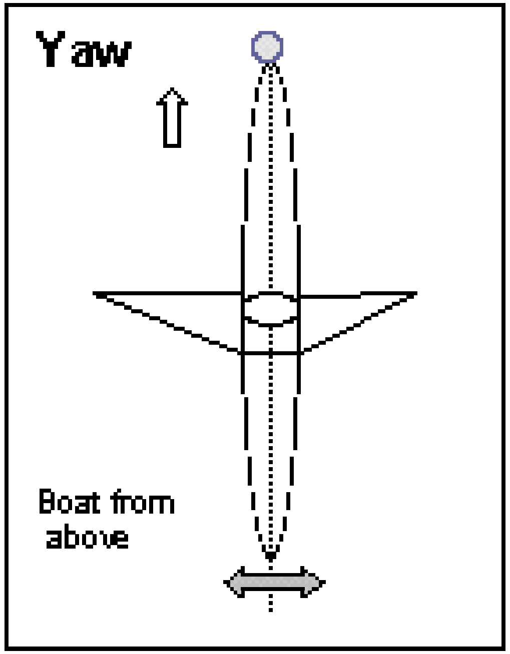
- Idea patented in 1870s
- Functional model built in 1950s
- Further developed by Volker Nolte and Empacher in early 1980s
- Kolbe won WCs in 1981 with sliding rigger
- Top 5 1x finalists used sliding rigger in 1982.
- Outlawed by FISA in 1983 due to “high cost”.

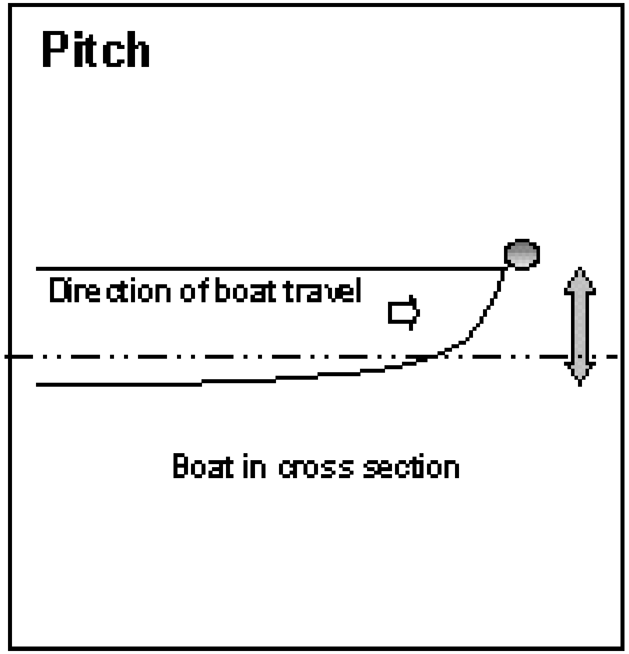
From: Miller, B. The development of Rowing Equipment. http://www.rowinghistory.net

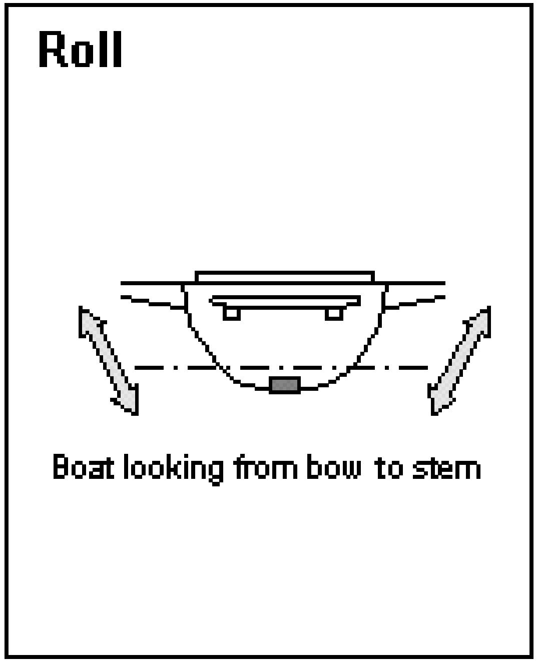
How much speed could be gained by reducing velocity fluctuations by 50%?

- 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 4-5 seconds in a 7 minute race.
- **Sliding rigger effect probably bigger!** due to decreased energy cost of rowing and increased stability (an additional 5s ?)

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

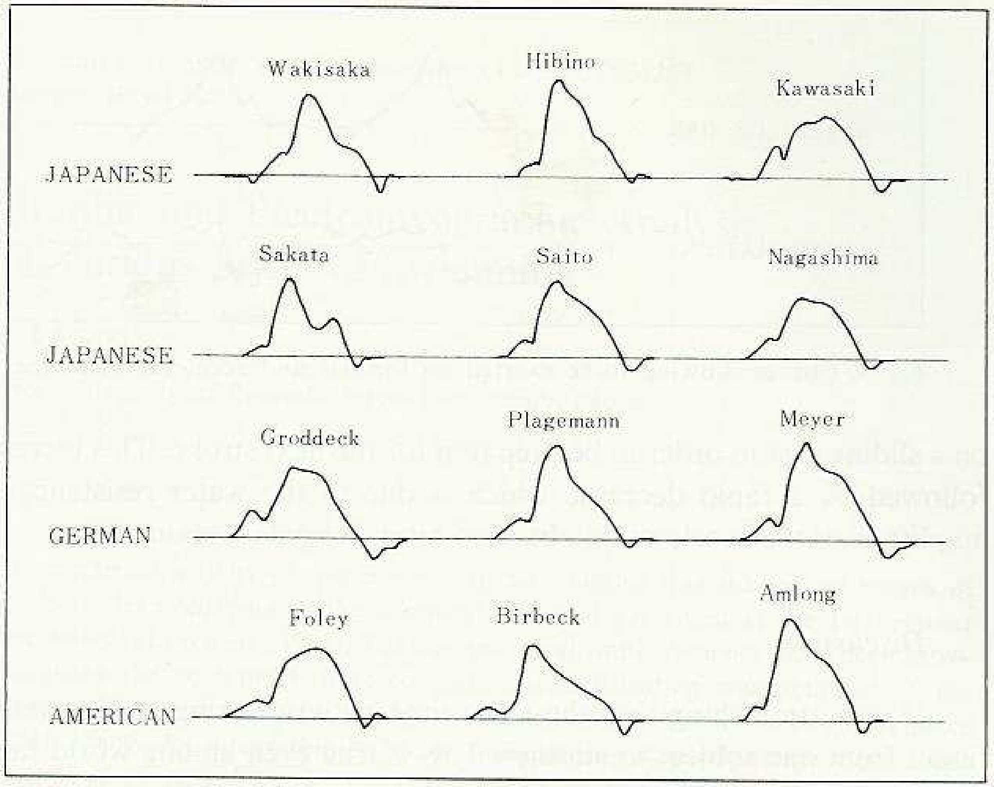
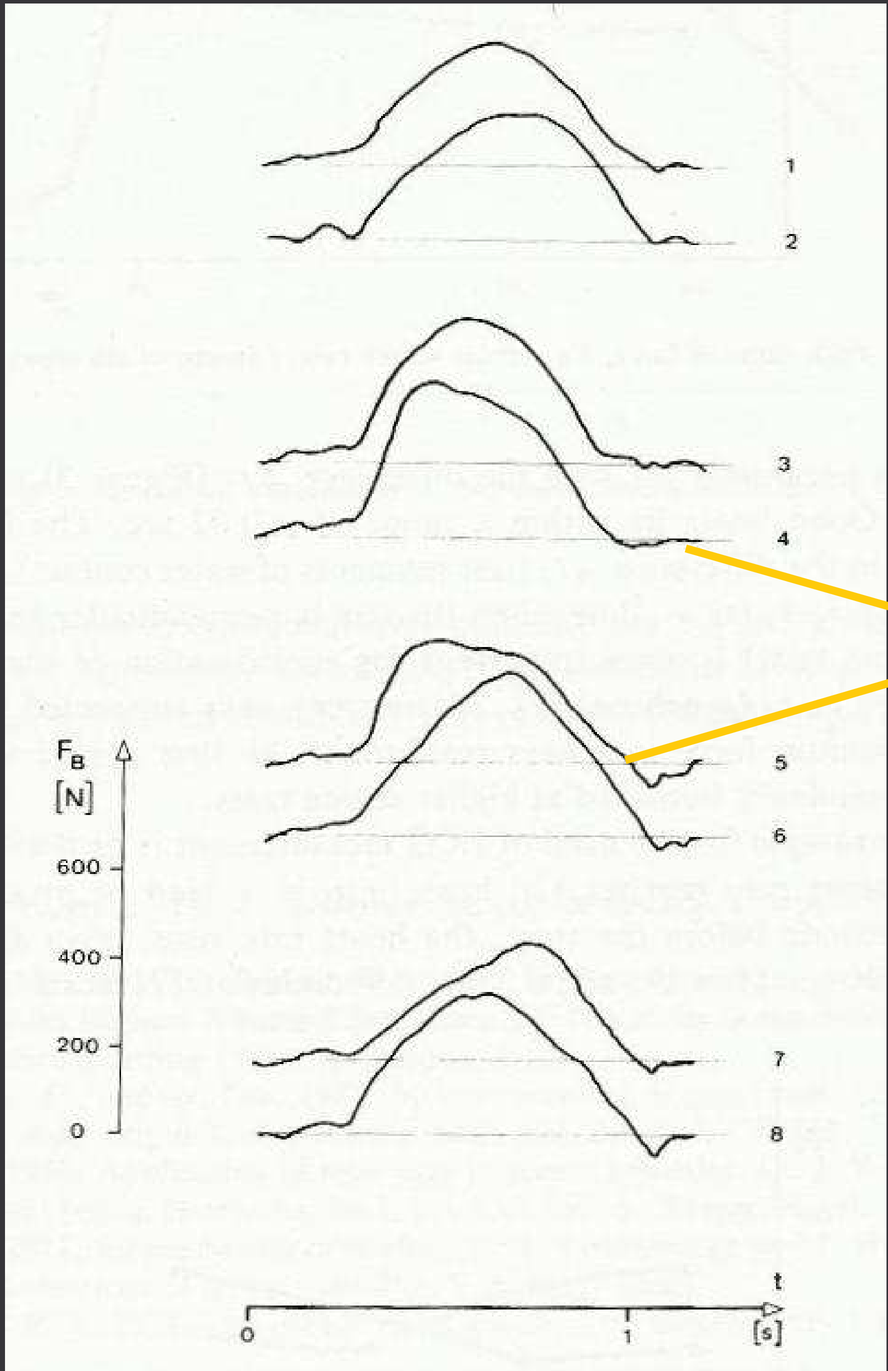


Fig. 2. Examples of force-time curves measured at the oar, by Japanese, German and American oarsmen.

"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"

"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

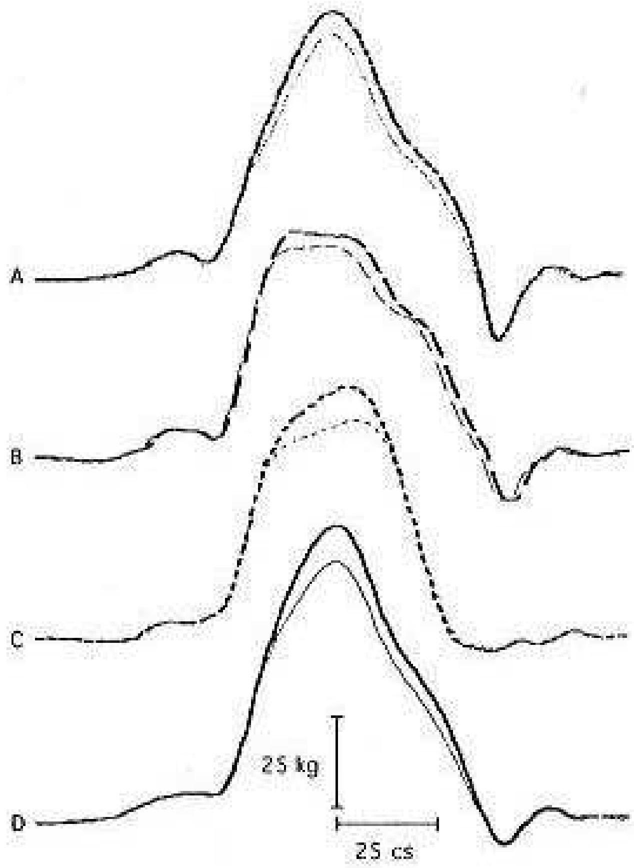


Figure 4 Ensemble-averaged ($n = 30$) force–time profiles for rowers A–D over two epochs, the second (faint line) some 3 min later than the first (bold line).

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.

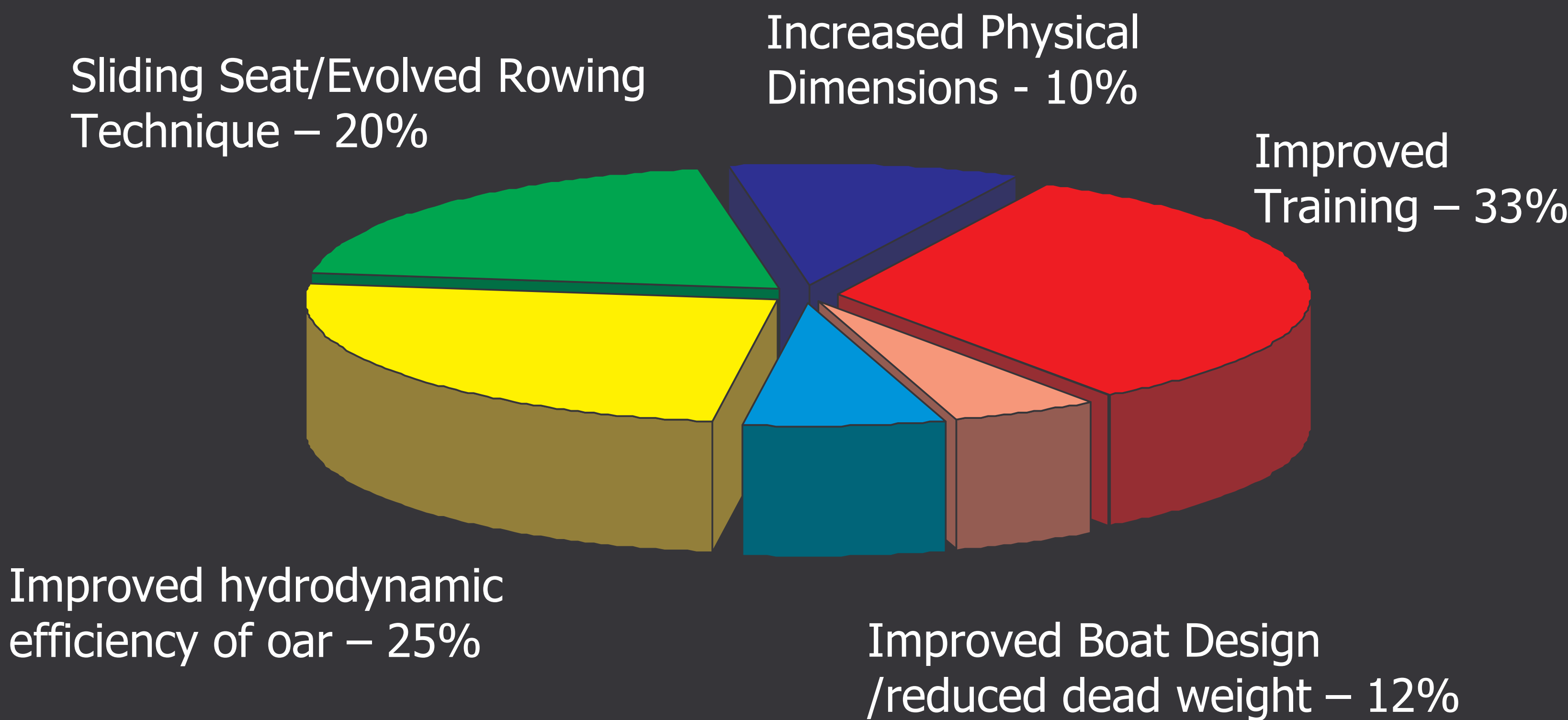
From: Wing, A.M. and Woodburn, C. The coordination and consistency of rowers in a racing eight. Journal of Sport Sciences. 13, 187-197, 1995

Is there an optimal force curve?

- For a 1x sculler: perhaps yes, one that balances hydrodynamic and physiological constraints to create a personal optima.
- For a team boat: probably no single optima 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



Thank You!