Physics – Mechanics for Rowers – 03/15/15

By Jim Dreher

Read this first - The summary conclusion:

To row fast, one must be efficient. We know that our mass is fixed and that there is only so much force available for the race. To parcel this limited force over the race distance there is a certain minimum average velocity that must be achieved in order to win. This key dependent variable (velocity) can be determined by graphically plotting a variation of Newton's 2^{nd} law F=m•a in real time and using the display as feedback. Restated F=m•a becomes the Impulse/Momentum equation F•t=m•v. Momentum (m•v) can be graphically observed as the size and shape of the area under the (F•t) curve. This graphical description of a physical quantity is shown in real time in the rowing tank or in the boat where the data is recorded for later observation. The Handle Speed curve is another curve that shows the angular velocity of the oar in relation to oar arc, in real time. The curve's shape shows when and how, to economically increase velocity and thereby increase or conserve momentum.

Making the rowing stroke more efficient using basic Physics mechanics and real time feedback with a graphical representation of Force

Two self-reinforcing subjects are to be discussed: One is how to use basic physics mechanics to develop an efficient rowing stroke and the other is how to use the rowing stroke as a model of a "real world" physics application for STEMD (science, technology, engineering, math and design) students who also may coincidentally be competitive rowers. By using the rowing stroke as an applied mechanics rowing "lab", it becomes an introduction to physics as well as a beneficiary of physics.

The intent is to weave the two subjects together right from the beginning so if physics is not in your current repertoire; any introductory physics text that does not require calculus as a read along reference, or the Kahn Academy physics series and Wikipedia will work.

Preamble: At DBC we have had a data logger type Force measurement system for almost 10 years. It is the Peach Innovations "PowerLine system" made in the UK. The in-the-boat display system shown above is the (not for sale) exclusive German system made by FES. We have used the Peach system to coach and test hundreds of rowers from Olympians to novices both in the boat, and for the last 4 or 5 years in the rowing tank with a real-time graphical display attached to the data logger. We have learned a lot about force measurement and continue to learn. We have come to the conclusion that the only thing holding back wide adoption of this technology is the basic education on the physics behind the hardware and what the graphical display of force shows us.

We first recognized this education gap in 2009 when we gave a presentation at the Jim Joy Coaches Clinic. That paper and slides are included here as an appendix.

This look at physics as applying to rowing is potentially most beneficial for the younger rower, in Secondary School, or University, who is perhaps interested in how the physical world works and a STEM career path.

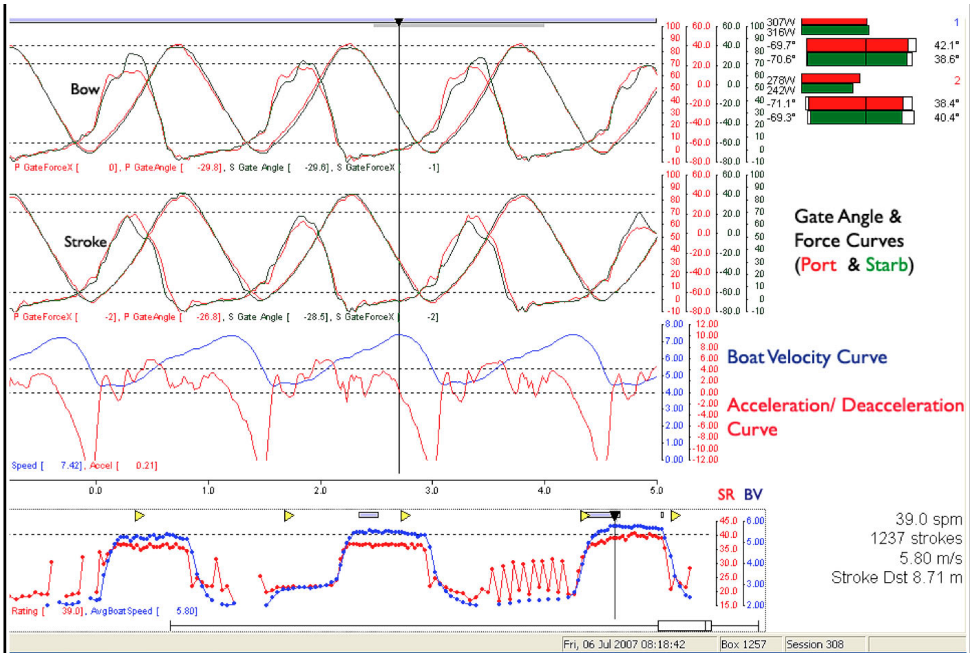
Our long experience as rowers, coaches, and engineers leads us to believe that the future of force measurement is for it to become both a avatar coach and teacher through real-time graphical feedback in the boat or the rowing tank.

Physics theory relies on empirical observation, which in turn requires defining and measuring physical quantities. Any physics text will start with a description of mechanics using mathematics to describe physical quantities. There are only four basic physical quantities in mechanics: **Force, Mass, Distance and Time.** All others such as velocity, acceleration, and concepts such as Impulse/Momentum, Work/Energy etc. are derivatives or products of the basic four.

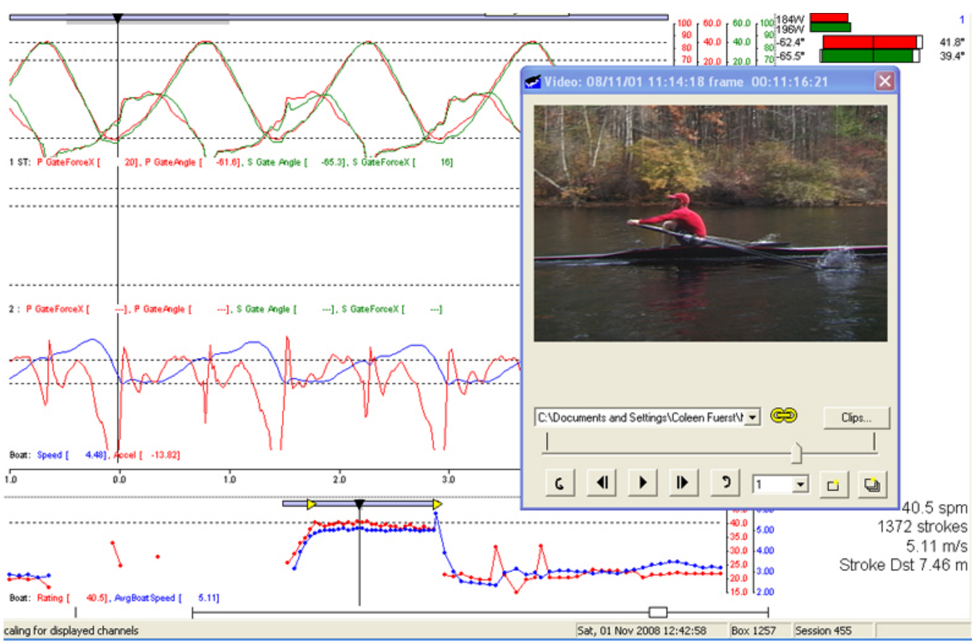
We can define and measure any physical quantity or concept with numerical data and/or graphical data. The easiest and quickest route to rowing technique efficiency is to use graphical descriptions of physical quantities and concepts in real time. This gives us instant feedback while rowing in order to master the optimum-rowing stroke. That is what a Force Measurement System is meant to do, that is; in be a coach of rowing stroke efficiency in real time, instantaneously defining, measuring and graphically displaying the motion.

Graphics works better than numbers or spoken instructions because it can be acted on directly without need for interpretation and the results are shown in real-time.

Introduction to Force Measurement:



Typical FM print-out from data logger for a men's HW 2x



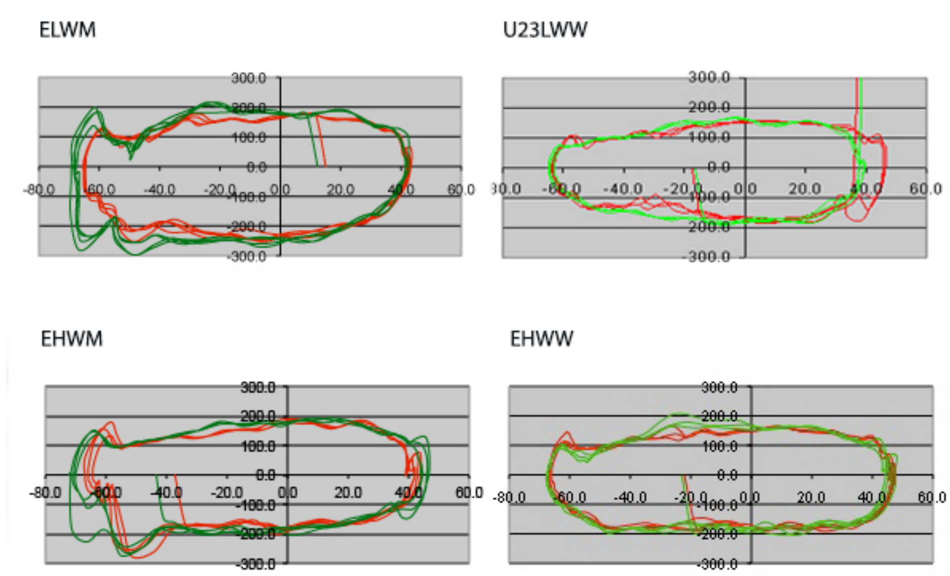
Shown directly above are 2 screen grabs taken from a force measurement system data logger printout. One is of a double and the other of a single with video syncing. Referring to either: The very top graph(s) shows a large red/green sine wave. That is the gate angle curve. The somewhat smaller and more irregular graph intertwined with the gate angle curve is the boat/rower momentum curve, which plots force vs. time. In all cases the red and green curves are data from port and starboard transducers.

The next set of curves directly below the gate angle and momentum curves, is the boat velocity curve (blue), and the boat acceleration curve (red). Superimposed on the graphical data for the single, is a video picture of an elite sculler at a high racing cadence (40.5 spm, 5.24 m/s). The momentum curve or graph represents the sculler's change in momentum, and is made up of an amalgamation of infinitesimal single points on the graph recorded at 50hz =.02 sec. per point plotting force vs. time. The area under the curve is the boat/rower system change in momentum according to the Impulse/Momentum equation (F•t=∆m•v)

The vertical black line is the instantaneous point in the stroke synced with the screen-grabbed picture, which in this case is at the catch as confirmed by the picture. The vertical axis of the graph is force in Newtons, and the horizontal axis is time in seconds.

The area under the (F•t) curve represents change in **Momentum** (∆M•v), or the area under the same curve could be thought to be **Work** (F•d). In that case the area under the curve would represent total **Energy**: the sum of **potential** and **kinetic energy**. If we divide the energy by time we get **power**. Viewing the area under the curve as momentum, energy, or power, the larger the area under the curve, the better. The shape of the curve should approach a half circle or parabola in the boat, and will be more rectangular shaped in the rowing tank.

An **Impact** type catch can be seen graphically by the steep slope of the curve at the start of the F•t curve, which indicates stored energy in the bend of the shaft acting like a spring



The four handle speed curves shown above are of 2 Olympic men – 0ne light, one heavy, a 4 time heavy Olympic women (2 gold, one bronze), plus one under 23 lightweight women sculler.

Do not confuse the curves of handle speed for a trace of the oar handle path. Although there is some graphical similarity there is no physical similarity. Each individual handle speed graph plots oar angular velocity vs. oar swept angle showing instantaneous handle speed at each point along the 360°travel of the arc of the oar, during both the drive and the recovery. The top half of the curve, representing the drive and the bottom half, representing the recovery roughly mirror each other. At any point along the curve the slope of the curve shows the instantaneous rate of change of velocity, or handle acceleration, by how steep the slope of the curve is.

Focusing on the top left hand handle speed curve, (the ELWM, which is considered the closest to an ideal, or "model" curve); the far left hand slope of the curve is practically vertical, indicative of a fast vertical blade insertion, matching boat speed. Right after the catch there is a small peak in velocity, indicative of a **Impact type catch** which can also be seen graphically by the steep slope of the curve at the start of the F•t momentum curve as well as the small spike in the boat acceleration curve. This direct graph comparison is possible because this particular handle speed curve is taken of the sculler in the picture superimposed on the momentum curve, and is taken at the exact moment indicated by the vertical black line bisecting the gate angle, momentum, boat velocity and acceleration curves.

This impact type catch results in stored energy in the bend of the shaft which is acting like a spring and storing potential energy to be released later in the stroke as kinetic energy.

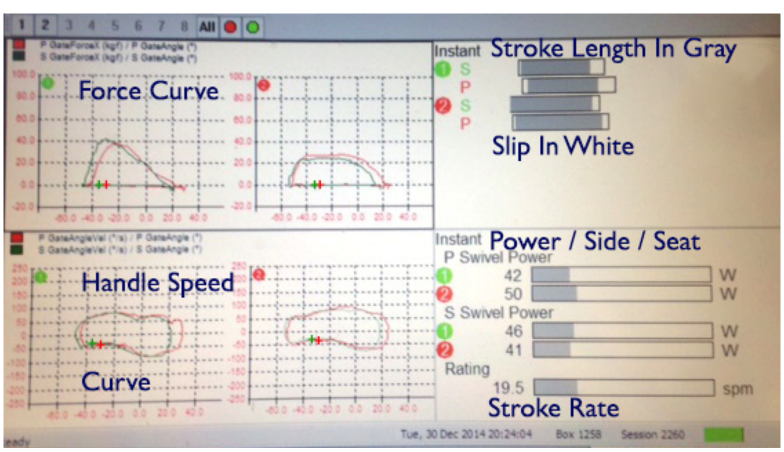
Initial peak of velocity: The curve shows that the initial peak in oar maximum angular velocity is followed by a threshold point of minimum oar angular velocity. If you look at the other three handle speed curves, which are unique to each athlete, they are all governed by the same minimum boat speed that occurs at the same point in the stroke cycle irrespective of rating, power, energy, or momentum. This occurs with each and every stroke and with each and every rower. This is due to the rower's kinematic limitations resulting in a momentary isometric effort when little or no work is done, but with initial high internal energy costs until the kinematics of the boat movement allow for a quick leg thrust. Both the handle speed curve and the momentum (F•t) curve indicates that to maximize momentum, at this critical point in the curve the rower has only limited economical force available from the legs and must rely on some other method to try to increase velocity. Some will use an early movement with the back, some will "break the arms", all due to an intuitive sense of needing to maintain momentum. When done in moderation both methods will either alone or together show a smoother momentum curve and an increase in slope of the handle speed curve, indicting an increase in velocity (acceleration). However, this is very much an art and not a science. One must through trial and error determine what works best.

1st Part of Drive: This part of the drive roughly taking about .4 sec. and 40º of oar arc, (at 40 spm in the case of the sculler pictured) results in the bulk of momentum change, plus the greatest oar handle acceleration and angular velocity. During this time boat velocity increases very little, if at all. On the graph this occurs from just after the catch to where the gate angle curve intersects the momentum curve. Kinematically this is accomplished first with a quick leg drive that blends seamlessly into the back.

2nd Part of the Drive: completes the back swing with a strong acceleration finish of arms. The key thought process here is hand acceleration to the finish of the stroke – handle speed. Good handle speed will keep the angular acceleration up near 200 rad. until the end of the pull through. This will contribute about 1/3rd of the momentum. Boat velocity is steeply increasing to the average during this part of the stroke, partially due to the boat and rower mass becoming one as you near the end of the stroke.

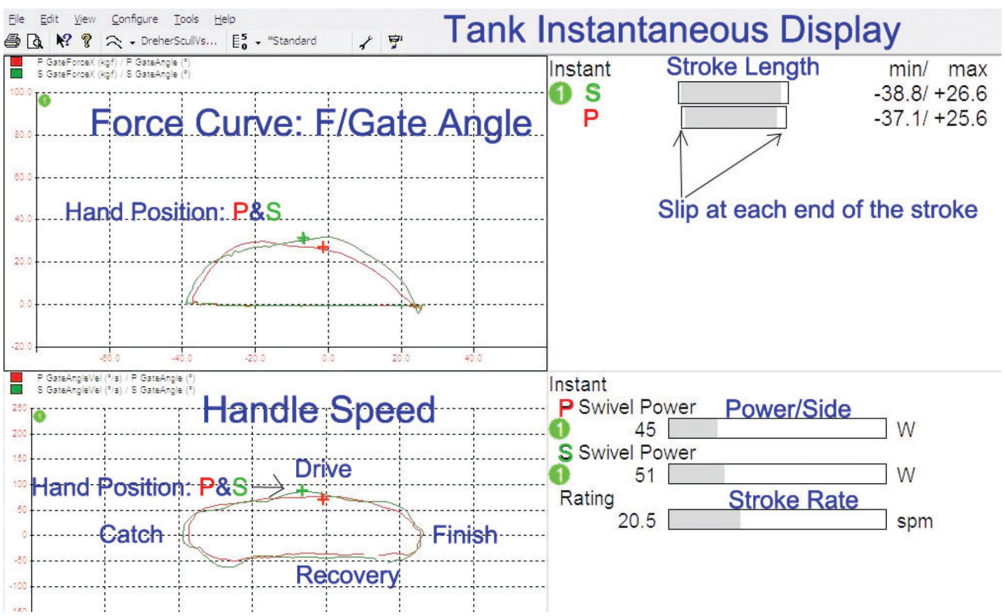
The Recovery: is all about preserving momentum without undue mass acceleration until just before and in conjunction with the catch. This is shown with the slight speed up in angular acceleration just before the catch on the handle speed curve. This is the lower part of the "little fish" tail.

The Rowing Tank: can simulate blade forces and momentum close to what is experienced in the boat. Shown below is a screen grab from a real-time screen display in the tank of two scullers rowing at the same time; each with quite different force curves and handle speed curves. In the tank the blade/water interaction being different from the boat requires that force in the tank be matched to what is experienced in the boat. In order to match forces, the blade, oar moment arm, and (pin) spread dimensions need to be modified to approximate the average force as experienced in the boat. The tank blade is designed to immediately slip relative to the water surrounding the blade while being resisted by the water mass perpendicular to the blade face, resulting in a force equal to what is experienced in the boat. In the tank we are deriving the momentum of the water pushed rather than that of the boat/rower system moving past still water. The momentum in the tank is the roughly the same, but differs from the boat in how it is derived. With constant force applied there results a rectangular momentum curve at start up until the velocity of the mass of water allows a slope at catch and release.



In the rowing tank the momentum of the water moved by the blade is the result of the force times the time when the blade is engaged with the water according to the Impulse – Momentum equation: (Impulse) Fxt=MV (momentum). As long as the force in the tank is near the force in the boat the simulation is successful. It makes no difference if the mass is represented as the boat/rower system, or by an equivalent mass of water resistance, as long as the force is the same the simulation succeeds.

The two tank screen shots, above (2 scullers)and on the next page (one sculler) have the salient charts, graphs, and numerical data labeled in large blue letters for identification. As you can see the screen is divided into four quadrants. The two left hand quadrants contains the Momentum curve directly above the handle speed curve so that relationship of the x-axis's are proportional for time on one and degrees on the other. Note that the handle speed zero y-axis is roughly in the middle of the graph trace, with the drive angular velocity being positive and clockwise, and the recovery being negative. The port and starboard hands are respectively red and green.



Introduction to rowing physics

The basic premise is that physics-mechanics quantities and concepts can be graphically displayed so that the rower can use these quantities and concepts to modify and mold their stroke through real-time feedback.

The ultimate objective in competition rowing is to row over a set distance in as quickly a time as possible using the limited force that the rower has available. This is not unlike Formula One car racing, except that F1 is 100% mechanical with force limitations in engine size, while rowing, unlike any other endurance/strength sport is just about even parts bio-mechanical and mechanical, with the rowers size, endurance and strength the limitation. In both sports: F1 and rowing, efficiency becomes all-important, and feedback on efficiency is essential for engineering an efficient racing car and an efficient rower. In fact: the force measurement technology used today in rowing had it's origins in F1 auto racing.

Physics is an empirical study of the physical world, and generally uses numbers to describe physical quantities such as force, mass, time, and distance. That part of physics is called mechanics, and it relates Force as proportional to Mass, Distance, and Time as F=Mass x Acceleration; with Acceleration being distance/time^2. This is Newton's 2nd Law, which neatly sums up the relation between physical quantities that must be efficiently deployed to meet the objectives of competition rowing.

Force and Newton's 3 laws: Force is a central concept of all Physics. It is defined as a push or pull on a body. In our case the oar handle is what we pull on and the stretcher and water pushes back. This is an example of Newton's 3rd law: "For every action there is an equal and opposite reaction".
Newton's three laws define the mechanics part of physics, which relates how force, mass and motion interact. When we pull on an oar handle we apply a force which according to Newton's 2nd law is defined and measured according to the proportion: force equals mass times acceleration, or F=ma. The 2nd law can be looked at as the 1st law (A body in motion stays in motion unless acted on by an outside force) when the resultant forces on a body are zero.

For rowing efficiency feedback only the very basic Newtonian relationship: Newton's 2nd law (F=MA) and the derivatives of that law such as: Impulse=ΔMomentum (Fxt=ΔMv) and Work= Kinetic Energy (Fxd=1/2Mv^2 need to be understood. Those concepts plus an understanding of the significance of the slope of the force/velocity curve being indicative of acceleration, and an understanding of the significance of the shape of the area under the curves being indicative of the size of Δmv, or the amount of KE, both of which are indicative of the efficiency of the rowing stroke.

Numbers and graphs: Physics is inherently a science of measurement. The physical quantities are usually defined and measured in terms of numbers (such as 3 meters per second as it shows on your NK SpeedCoach). To add dimension and further define the boat's speed it is useful to plot the various physical properties and their derivatives, such as velocity (the vector equivalent of speed, since it has direction), or acceleration, which is the change of velocity over time, or applied Force plotted against time (which defines Impulse/Momentum).

Graphics represents the physical system by a diagram (a curve) that can show a physical relation without need of numbers or an algebraic solution and which can display the results – potentially in the boat, or in a rowing tank in real time.

Inertia
It becomes obvious that while the total mass of the boat/rower system is a constant the individual masses of boat, plus oars, plus the mass of all the parts of the rower move most of the time relative to each other.

Slightly rearranging the 2nd law another way: F/a=m results in what is commonly referred to as inertia. Inertia is a concept of how to look at mass and its propensity to be moved by an unbalanced force. The Inertia concept shows that mass is proportional to force and to the reciprocal of acceleration. The movement of the rower's mass generates a very considerable force. It is considered to be an internal force in the system resulting from the relative movement of the boat relative to the rower in about a 1 to 6 ratio of masses of boat vs. rower. The cyclical, sine wave signature of the boat velocity is the evidence of the domination of the rowers mass and resulting inertia on the total system mass.

The inertia of each component of all the freely moving parts of the boat/rower system could be explored, either mathematically or graphically, but would become very complex. It is far easier to record and display just the net force applied to the pin and the velocity of the boat in the direction of the finish line. The graphical record then essentially treats the boat/rower as a one-dimensional point source traveling in a straight line.

Rowing best practice is to try to minimize both the distance and speed of movement of the largest body masses (Inertia), but also to strategically use mass acceleration, just prior to and in conjunction with the catch as an efficient way of maintaining momentum, as we will see in the next section on Impulse/Momentum.

Impulse and Momentum, Conservation of Momentum, & the Catch
As mentioned above: The concepts of impulse/momentum and work/kinetic energy are derived from Newton's law of motion, F=MA. So it will come as no surprise that Work/KE and Impulse/Momentum are in a way similar concepts with a rearrangement of the same basic quantities and their products. The result is a proportional equation: Impulse equals the change in momentum $Ft=\Delta mv$.. Keep in mind that the area under the force time curve represents the total momentum of the system.

As we just alluded to under the INERTIA section: a best practice is to maintain momentum with a well-timed speed up of the rower's mass in conjunction with the catch. For rowing the ($m\Delta v$) momentum equation exactly defines the best practice motion leading up to and taking the catch in order to maintain momentum.

The catch can also be modeled as Newton's 3rd law: "For each action there is an opposite and equal reaction". The 3rd law defines the motion of solids, such as billiard balls being struck and rebounding (collisions- see Impact below), and we take some license to use it to define the most efficient motion that an oar blade should take when coming in contact with the water. The total momentum of water and blade is constant in keeping with the 3rd law as expressed in the principle of conservation of linear momentum: **"Baring outside forces; The total momentum of a system** (water and blade) **remains constant in magnitude and direction".** The impulse/momentum equation tells us that a "best practice" catch must be <u>quick</u> (collision time must be short, which is essential to get the blade anchored into the water quickly) and must also be deep (so that there is no movement relative to the water), it follows that the initial force will be high. This Impulse {F•t) creates a large change in momentum thereby increasing velocity in the direction toward the finish line. This can be seen as a spike in boat acceleration and a large change in momentum when an impactful catch is made. This is shown on the force measurement data on page 2. And a picture of an impact type catch is shown on page 9.

To reiterate: Conservation of momentum points towards favoring a slight speed-up on the very last part of the slide (+ΔV) toward the stern coinciding with a quick, vertical insertion of the blade and resulting in a high initial force.

Impact is described as impulse of 2 bodies experiencing rather large contact forces during a short interval in time. With not too much a stretch of the imagination this concept can be used to describe what takes place during the ideal, or most efficient catch.

In the boat, when the full face of the blade meets the large mass of water at a high enough velocity very little relative translation of water occurs. The water is not moving, so it has zero momentum. Relative motion of the water relative to the blade face from begins immediately, but this is across the blade face (tip to tail) if the blade has been inserted quick enough. The product of force on the blade and time is linear Impulse and it is equal to the change in linear momentum. The impact of the boat/rower system is taken at the catch. Catch Impact can be seen graphically by the steep slope of the curve at the instantaneous start of the Force Time curve with the duration shown by the area under the curve, which is equal to the total change in momentum of the system according to the law of conservation of momentum.

The above picture shows a quick, deep, impact type of catch. No water movement is noticeable in the boat direction toward the finish line.

Work: If we were to replace velocity on the x axis of the Force*time graph with distance (using distance equals rate times time), than we have described work, which equals force times distance. We know that work equals kinetic energy, so by observing one graph taken from data in either tank or boat we can then describe 4 derivatives of the 2nd law: momentum, impulse, work and energy all of which can be explored to see how to row more efficiently.
In physics the term Work is defined as Work = Force times displacement. Work is a scalar quantity that characterizes motion. There must be movement or no work is done. The unit of work is the newton meter, or joule. It can be positive or negative algebraically. Work does not necessarily have the same direction as displacement. At right angles to the displacement it is of course zero. It is the component in the direction of the force that does the work, therefore the equation for work is: W=Fcos the angle x displacement. If we divide work by time we get power.

Energy When we use energy to evaluate the force used to propel a boat we refer to both Potential Energy PE (the energy of position), and Kinetic Energy KE (the energy of motion). KE is defined as ½ mass x velocity squared. This is a scalar quantity and is only dependent on velocity and not it's direction. $Fxd=\Delta KE$. Work equals the change in Kinetic Energy.

Another way of looking at the total efficiency of the stroke is the conservation of energy of the colliding masses at the blade/water interface. Again, this is sort of a stretch, but ideally the ΔKE and ΔPE of the system total zero if friction is ignored. Total energy before impact (the catch) is divided into three parts after impact. Rebound energy is one part, heat and vibration are the others (which certainly can be ignored in rowing). Rebound Energy of the oar shaft acts very much like a spring. The spring effect is hard to quantify but we know from observation that there is a quantity of stored energy in the bend of the shaft. This should make a case for continuing to apply force with increasing handle velocity until the end of the stroke. This stored energy in the bend of the shaft can best be thought of in terms of the conservation of energy or the capacity to do Work by motion (Kinetic Energy) or position (Potential energy). The potential energy can be subdivided into elastic energy of deformation and position. Position usually refers to gravitational energy, which for the most part we are not concerned with when rowing. Elastic energy due to deformation, or strain energy is energy stored due to an elastic deformation, in short: a spring, which sort of characterizes the oar shaft bend. For a spring compressed an amount x, the elastic energy V=1/2kx^2 for a spring constant k. This represents the work done to compress a spring or bend a carbon shaft, and our internal energy ready to be used at full leg compression. This is all potential energy of position. All the energy stored is potentially available to do work, until the oar is unloaded at the end of the stroke. Looking at the graph; for this to represent Work/Energy requires us to mentally replace time with stroke distance on the x-axis. Then the area under the curve becomes the sum of potential and kinetic energy. Again: more area under the curve is better. The shape of the curve in either case should approach a half circle or parabola in the boat case (due to boat velocity and acceleration) and be more rectangular shaped in the tank (due to no boat acceleration relative to tank water mass).

Getting back to the definition of Work as the model for the rowing stroke: Conservation of kinetic energy will be a byproduct if we treat the first part of the drive as an isometric (with the initial high Force mainly from the legs) until the kinematics of boat movement favors a quick leg thrust. Easier said than done, but basic physics-mechanics principles shows that should be the most efficient description of an efficient rowing stroke. Both the Work-Energy and the impulse-momentum equations are based on conservation of energy. Each side of the equation is proportional and equal to the other.
One concept has force times distance equal to Kinetic Energy. The other has Force x time equal to mass x velocity. All that has been done is rearranged f=ma in terms of two new concepts quantities called Work and Impulse. Both concepts can be used to describe an efficient rowing stroke. Frankly, I think that the Impulse/Momentum concept is more intuitively useful than Work/Energy when trying to describe an efficient rowing stroke.

Graphs: As just discussed above: as an alternative to a numerical description of physical quantities and concepts; a graphical description works best. Graphs (curves) have value in being able to be acted on in real time. By observing the graphical rates of change and areas under the curves while rowing the rower can attempt to replicate an "ideal" model curve shape that can be constructed using basic physics mechanics. Graphical displays show much potential benefit for efficiency training in the sport of rowing.

As a guide to constructing a model graph or curve it is a best practice to first study some of the curves of some of the best rowers in the world. The best conceptual curve studied (in my opinion) is that of the basic equation of **Impulse/Momentum** ($Ft=\Delta Mv$). Total change in momentum is area under the force x time curve made by the rower. The impulse /momentum equation indicates that the goal is to maximize the momentum, which relates to the size of area under the curve.

Ha**ndle Speed**, which plots oar angular velocity vs. oar angle is a continuous curve that shows instantaneous handle speed at each point along the travel of the arc of the oar, during both the drive and the recovery. As such, by way of the moment arm (the oar), the curve tracks the blade angular velocity as a direct proportion to it's center of pressure to the pin (fulcrum) distance vs. the centerline of the boat to the pin. This graph is very telling because as the first graph (impulse/momentum) has shown, blade velocity is all-important. The superposition of the handle velocity curve directly below the Impulse/momentum curve relates how blade velocity is a direct function of boat velocity, during the time that the blade is engaged with the water. This curve is very powerful because it directly shows the effect of the two variables available for us to change – distance (oar arc) and velocity (oar speed), and we can graphically see oar acceleration and catch quickness, all in one 360º graph showing the entire stroke – the drive and the recovery.

Superimposed directly below the gate angle curve and the impulse/momentum curve is the handle speed curve (which has a shape reminiscing a snack-food "little fish"). This graph charts handle angular velocity as a function of oar swept angle. It charts the full 360º of the stroke cycle. The horizontal axis is the zero velocity datum. Velocity magnitude is delineated in "radians", with one radian equal to the circumferential equivalence of the radius, with 2π R=360º= 6.28 radians/360º. Acceleration is defined and measured in terms of velocity divided by time, or rate of change of velocity. It becomes obvious that up is positive angular velocity on the drive and down is negative angular velocity on the recovery. When done correctly the parts of the curve, representing drive and recovery roughly mirror each other. At any point along the curve the slope of the curve shows the instantaneous rate of change of velocity, or handle acceleration, by steepness of the slope of the curve.

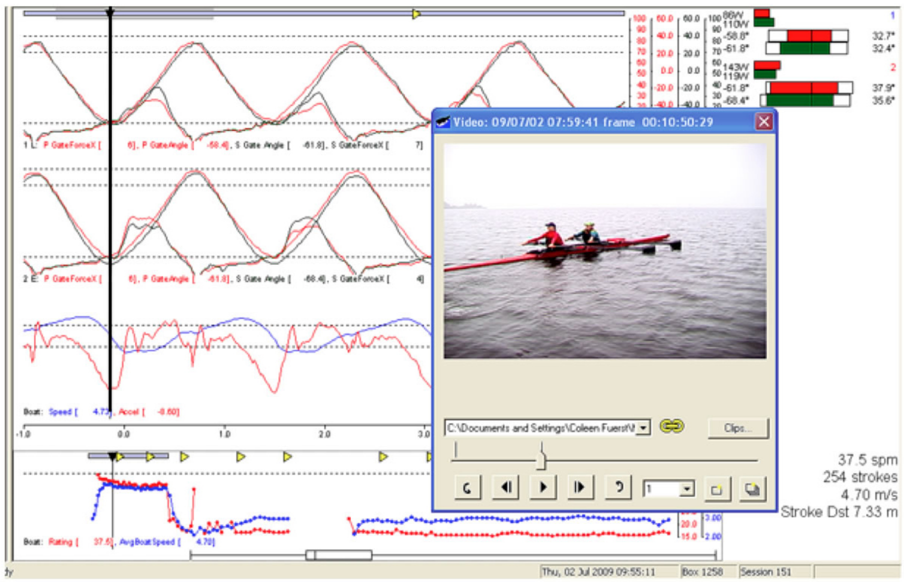
In rowing the position of the blade in the stroke cycle is completely specified by the angle of the oar in reference to the bow to stern axis of the boat, with oº being when the oar is perpendicular to the axis with -70º about the maximum catch angle, and 40º about the finish angle for sculling. For sweep: about -60º and 40`º. With elite scullers, both light and heavy, men and women, the maximum radians per min. handle velocity we have seen were about 200 and the minimum about 100. Not surprising was an apparent threshold of about 100, independent of rating and athlete class immediately after the catch when the blade is locked in the water and governed by the minimum speed of the boat past the still water. This illustrates the futility of expending too much energy expense in an internal isometric that is incapable of doing productive work at that point in the stroke until the leg angle is in a more powerful position. This is the point just after a quick, deep catch that we momentarily "hang" with arms loosely extended with about 70% pressure primarily derived from the legs.

Note: the black line on the handle speed chart is the zero degree oar angle and is not the same as the long black line that shows the catch position in the picture and links the gate angle and impulse/momentum graphs to the same point on the bottom boat velocity and acceleration graphs.

At the bottom of the FM report is shown the graph of the boat acceleration curve (red) and the boat velocity curve (blue). The bottom horizontal dotted line is the zero acceleration line. The x axis is always time,(except when we arbitrary substitute distance for time if we choose to illustrate work, or energy under the curve. A key point to note is that the acceleration should not go negative during the drive. Also it should stay positive as long as possible on the recovery, and when it does go negative it should be steep and of short duration, just before the catch. The boat velocity should also have a positive upward slope for as long as possible.

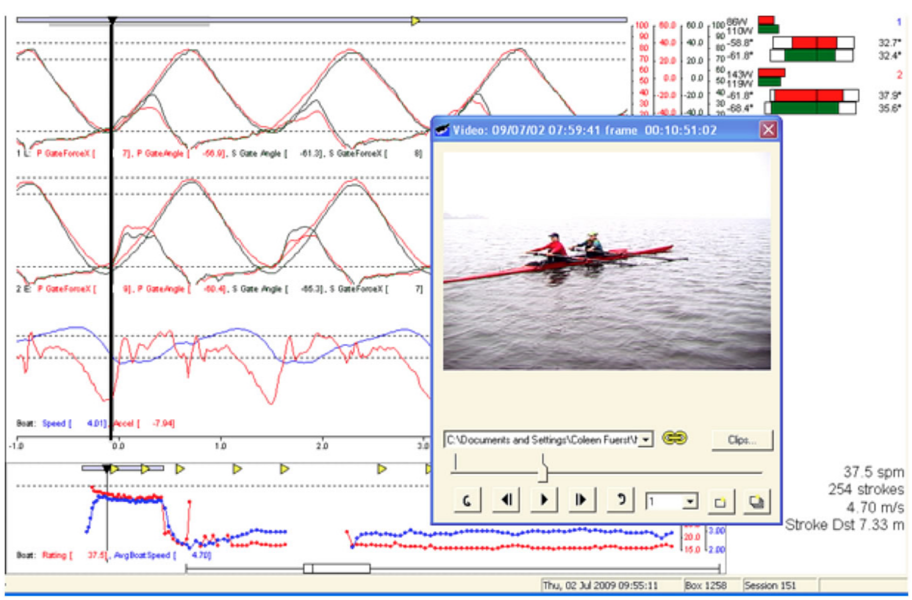
The tale of two doubles: The 12 boat FM report data curves reproduced below graphically show salient points of the previous discussion. The first report shows an under 23 light women's double at the maximum gate angle (furthest stern position), as evidenced in the video and indicated by the black vertical line cutting through the graphs. The oars are fully squared and about to be inserted into the water. This is the 0ºgate angle curve position, the bottom of the boat acceleration curve (red), but not yet at the lowest part of the boat velocity curve, and force is also zero.

U23 LWW2x: Max. Gate Angle - Catch



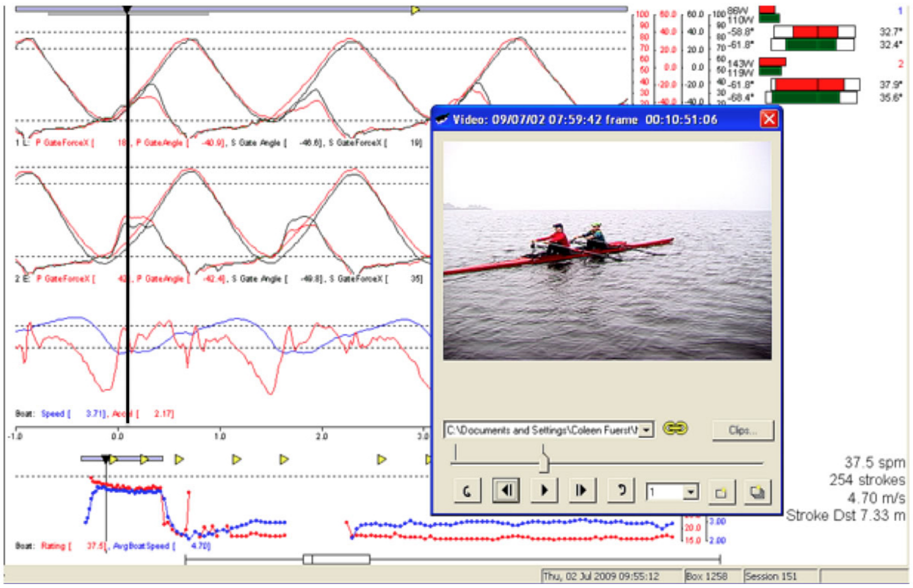
The next graph shows that acceleration has just started, along with force just starting to be applied, however the stroke length bar chart shows a large slip (slow catch) from the bow position relative to the stroke and the video reveals a corresponding not fully buried blade at bow.

U23 LWW2x: Angle at True Catch

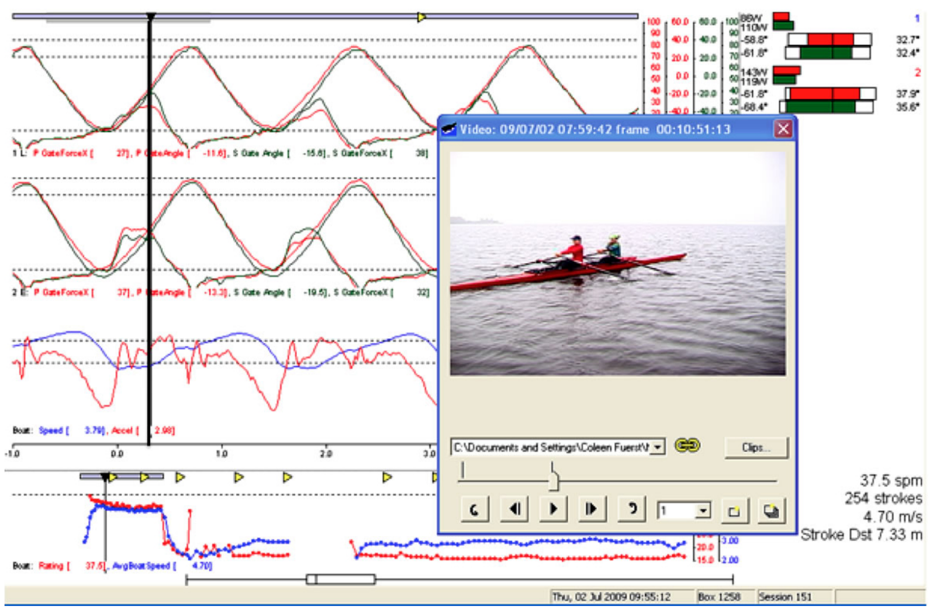


The next two graphs show the major discrepancy between the two scullers in their initial peak force application indicated by the black line.

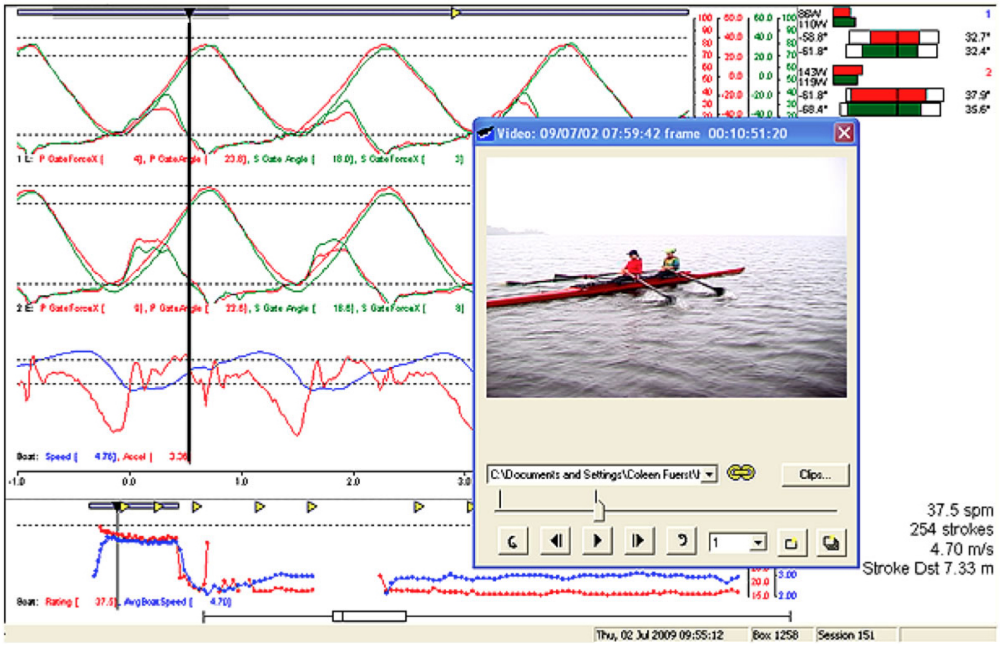
U23 LWW2x: Peak Force - Stroke



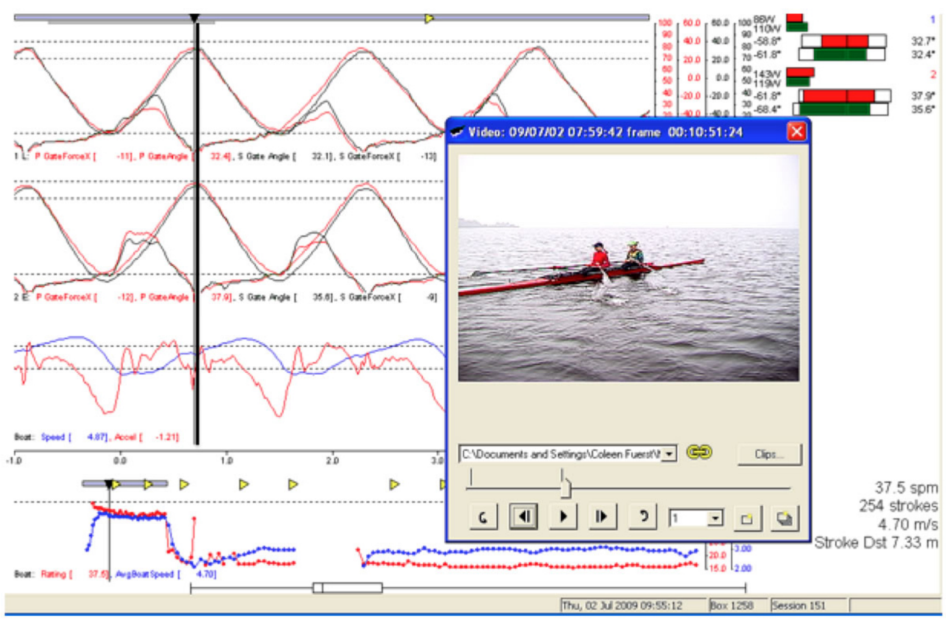
U23 LWW2x: Peak Force - Bow



U23 LWW2x: Angle at True Release

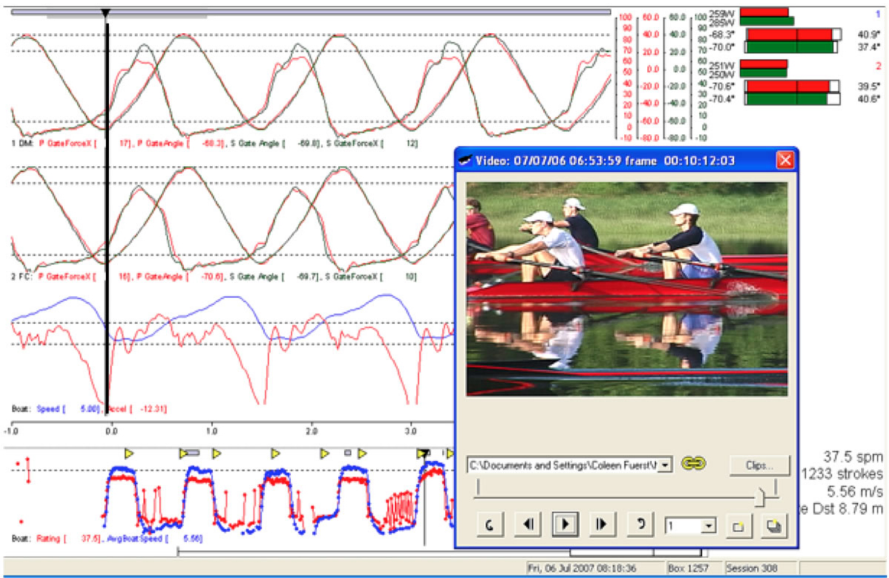


U23 LWW2x: Maximum Gate Angle Release

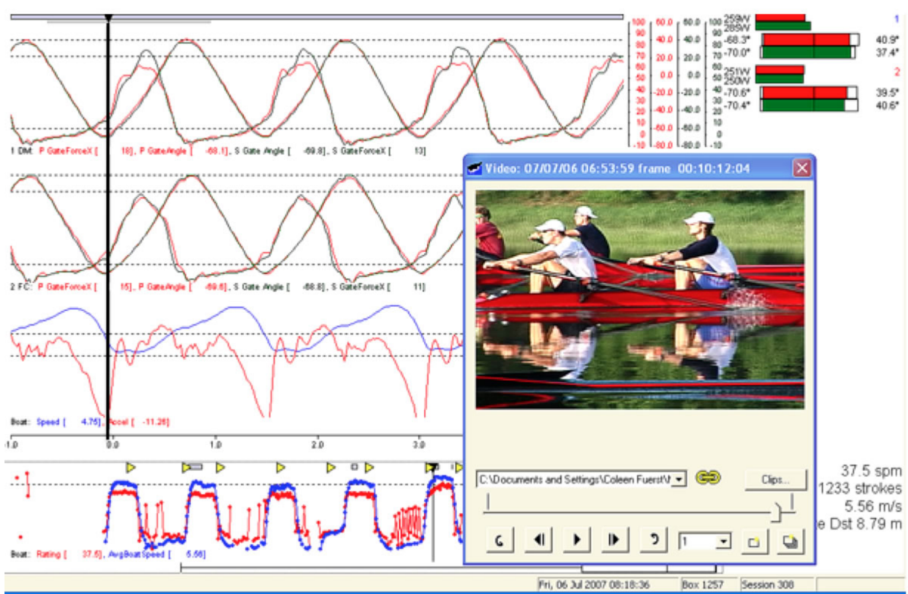


The first thing to notice about the heavyweight men's double is how quick their catch is, with the maximum gate angle and the true catch being virtually indistinguishable on the graph or in the video. Only the hands raise with no other body movement. The stroke length bar chart confirms that with very little or no white area showing at full extension of -70º.

HWM2x: Max. Gate Angle - Catch

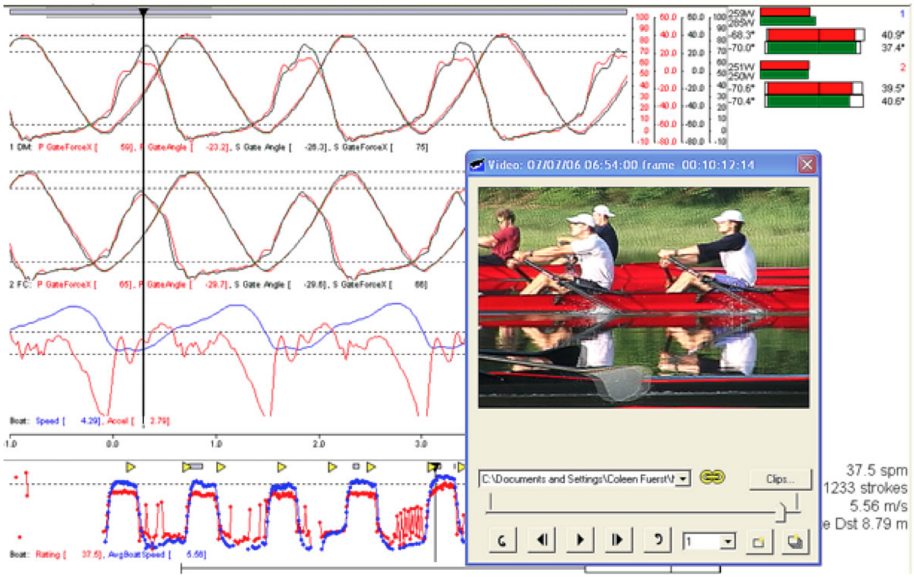


HWM2x: Angle at True Catch

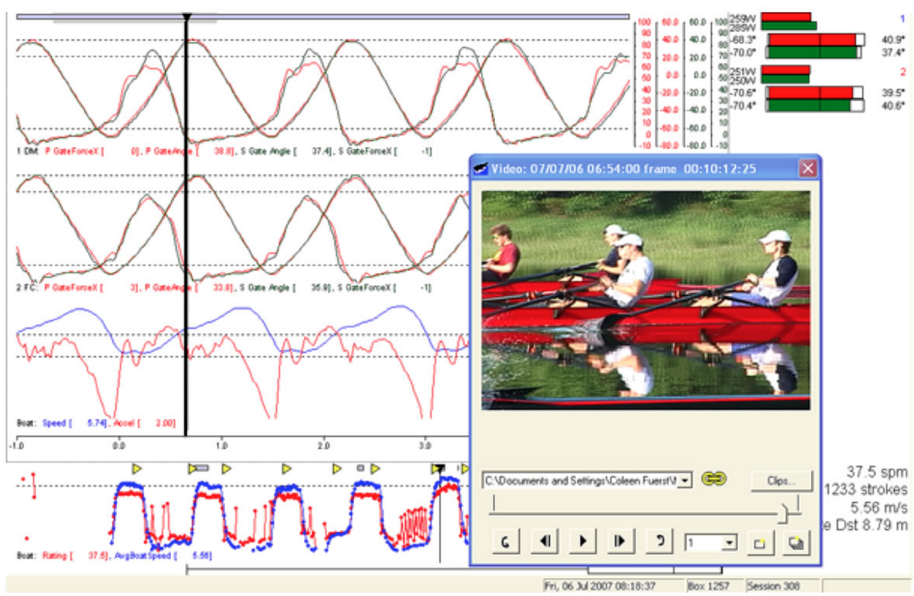


Peak forces are matched well, even though the two scullers are slightly dissimilar in force curves, with the stroke being somewhat simultaneous and the bow being sequential. Leg kinematics are identical.

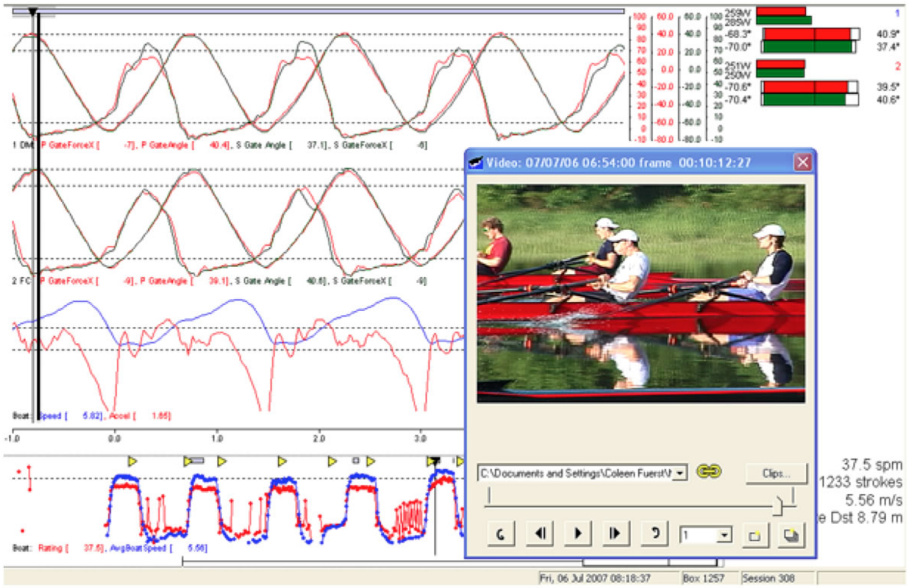
HWM2x: Peak Force



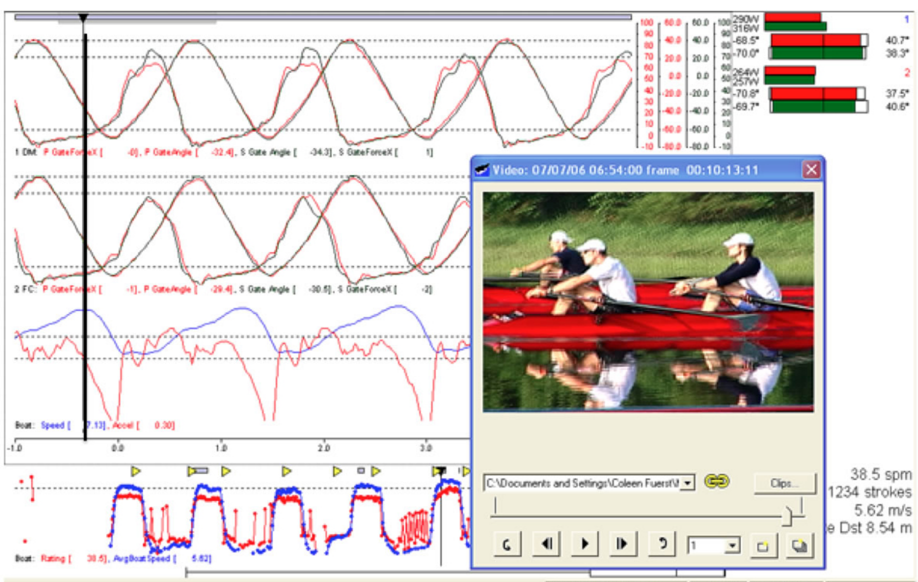
HWM2x: Angle at True Release



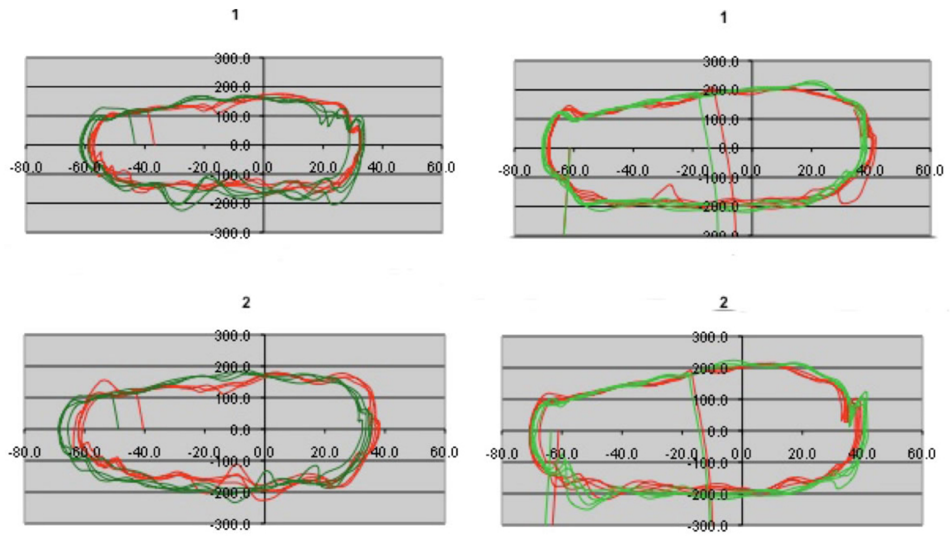
HWM2x: Maximum Gate Angle: Release

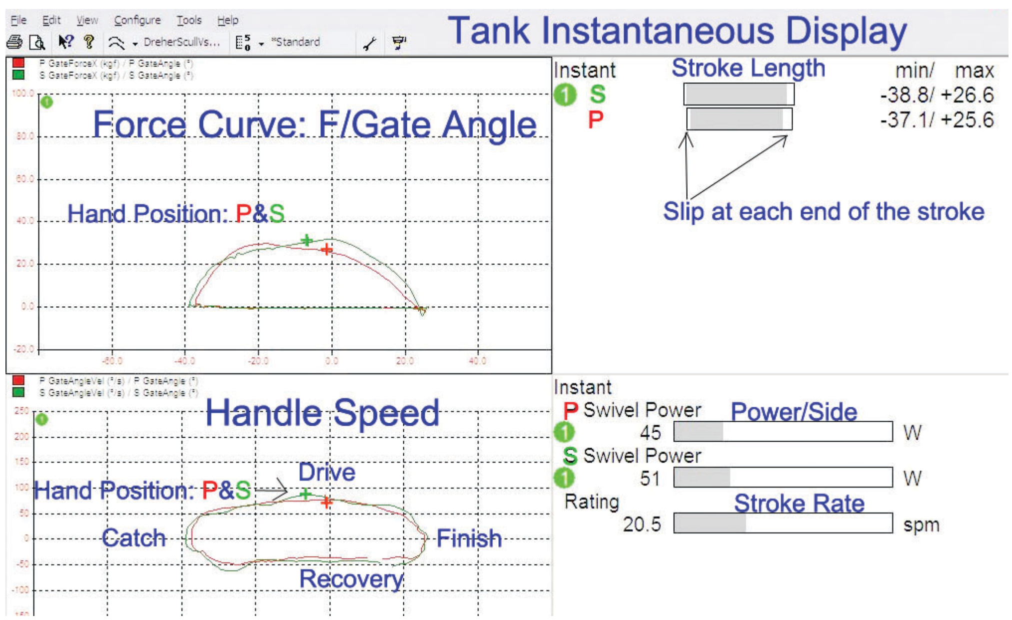


HWM2x: Maximum Boat Velocity



U23LWW 2x **Elite HWM 2x**





Graphs in the Rowing Tank: Real time instantaneous change in rowing efficiency can be obtained better still in the rowing tank. The tank allows us to focus on the mechanics of rowing without environmental distractions. In the tank, the data is displayed in four quadrants: In the left half of the screen in the upper quadrant is the Impulse/Momentum graph. The quadrant directly below contains the Handle Speed graph. On the right hand half of the screen in the top quadrant is a bar chart showing the total stroke length, the quickness of the catch and the synchronization of port vs. starboard if sculling. The fourth quadrant at the bottom right contains numerical data such as power in watts, both total and port vs. starboard, and stroke rate. It is hard to multi-task and focus on more than one of the four quadrants displayed at a time.

The tank situation is completely different from the boat with the blade, moment arm, and fulcrum dimensions modified to approximate the average force required. The tank blade, is designed to immediately slip relative to the water perpendicular to the blade face and with constant force applied results in a rectangular curve until the momentum of the mass of water allows a slope due to lack of catch quickness, depth or both.

Boat vs. Rowing tank discussion: The boat movement is recorded using the water as the stationary reference point that does not move. The boat moves relative to the large mass of still water. It matters not if the water has current. Relative to the water, the blade of the oar, although moving through the water around an axis (pin) that is translating relative to the water, does not have much of a net movement past the water in the direction of the finish line while engaged with the water. Most of the blades motion relative to the water is resolved perpendicular to the boat during the drive phase.

Mass in the tank: In the tank the rower's mass moves back and forth relative to the pin, just as in the boat, but the rowers mass makes no net gain in distance relative to the mass of water, which just circulates. Rowing in a tank is akin to stirring a pot with a spoon. In the tank, just as in the boat, the force on the pin and the angular rotation velocity of the oarlock are recorded, but since there is no net movement of the rowers mass relative to the mass of water there is no acceleration. The tank is the absolute reverse to the boat/water situation, the oarlock does not move in translation relative to the total mass of water in the rowing tank. In the tank the blade moves relative to the water by moving through it primarily in the same direction as the flow and activates a relatively small mass of water, which in turn activates a small percentage of the entire volume of the tank with each stroke. This major difference between boat and tank necessitates sizing the area of the tank blade to shear through the water to create resistance.

In the boat the force that we apply to the oar handle is transmitted to the boat/rower system by way of the oar at the blade/water interface and resisted by the equal and opposite sum total of water and air drag forces on the boat/rower system. In the tank the only meaningful resistance balancing the force applied to the handle is due to the mass of water encountered by the blade. In the tank the blade area, outboard moment arm and the blades mechanical advantage is empirically changed to roughly approach the average force felt in the boat. In the boat water (85%)and air (15%) are the unbalanced forces slowing the boat down.

Momentum in the tank: In the rowing tank the momentum of the water moved by the blade is the result of the force times the time when the blade is engaged with the water according to the Impulse – Momentum equation: (Impulse) Fxt=MV (momentum). This is the equation we are trying to balance. In the tank we do this by reducing blade area and increasing the rowers mechanical advantage in an attempt to equate the force felt at the handle to what is felt in the boat.

Kinematics and Dynamics of rowing in the boat and in the tank: The above discussion trying to relate the rowing motion both in the boat and in the rowing tank to mechanics is referred to as Kinematics: this "geometry of motion" studies displacement, velocity, acceleration and time measurement coordinates, both linear and angular, without regard to force. If we plot force against either time or distance or oar angular velocity vs. oar angle the results are curves and areas under curves that tell us much about how we should row efficiently.

Kinematics is motion without regard to forces. Dynamics, or Kinetics is that part of physics that studies both motion and forces that results from motion. Rowing is dynamic: When you row you are in a repetitive cycle of speeding up, slowing down, reversing direction, all of which require a change in the magnitude or direction of velocity. As discussed the change in rate of velocity is acceleration. In rowing on the water both the body mass and the boat mass is accelerated as a result of forces due to the motion of the rower and the forces opposing that force due to both water and air friction. In the rowing tank boat acceleration does not exist but the kinematics are basically the same. The goal of the rowing tank is to simulate the forces as close as possible to what is experienced in the boat. The rowing station used with the tank is essentially a replication of your part of the boat fixed to the earth so no boat acceleration is possible. Still; the goal is to find out how to be most efficient throughout the stroke cycle. The real-time graph of force times velocity (Momentum) in the boat will be similar in the tank with the area under the curve in both cases being change in momentum. In the one instance it is change in boat/rower momentum and in the tank it is a change of water momentum, but ideally the force is the same in both cases and then momentum/time in each case will be equal.

Appendix: FORCE MEASUREMENTI - Jim Joy Presentation 2009

Biomechanics – Finding the optimum Stroke

To know the most effective or optimum force we must first measure the force. A Force Measurement System is needed to do that.

What force are we measuring? The rower creates the force to move the boat. Forces result from pulling on the oar while pushing on the boat and by the resulting rower's mass movement. The boat and oars are acted on by resisting forces due to friction of passing through the water and the air. Some of these propelling and resisting forces are not directly in line with the intended progress of the boat. If the forces applied, are not balanced by an opposing force, the boat will turn. In measuring boat-propelling forces we are only measuring **forces in the direction of travel**. To measure these propelling forces we have a choice of three places to measure: 1. The oarlock pin. 2. The foot stretcher. 3. The oar. The system that we use measures the resolved **force acting on the pin.**

History of Force Measurement

Force Measurement systems have been around for over 40 years. The first documented was the forces curves taken of the German eight at the Tokyo Olympics in 1964. The first thing that the curves showed was that all eight athletes applied force slightly different relative to each other even though to the naked eye they looked to row together perfectly. Another system was made by FES, the GDR sports research and development group during in the 70's and 80's. During the last 20 years there have been others by the Russians, Austrians, Australians and English. The German FES system is still available, but only at the German training centers. The Austrian and English systems are commercialized, each taking advantage of improvements in electronics technology and the decrease in component cost evolving toward a workable, but still relatively expensive system. To date all systems are used primarily for biomechanical research with the necessity of a biomechanics expert to disseminate and interpret the data for the coach and the athlete. All systems use either a radio telemetry system or an in-boat data logger or both to record data that is than downloaded to a computer with special software to produce graphs, curves and numerical data. This information is then shown along with the video some time after the rowing session to the coach and then to the athlete. The English system has video synchronized to the force data so that the force and the stroke kinematics can be studied together. Besides being expensive the systems commercially available are in their current configuration difficult and time consuming to use and maintain, and to analyze the data you need the assistance of a rowing biomechanics expert. Few programs around the world have the means to provide this specialized person to assist the coach and ultimately the athlete.

Necessity for Biomechanical Information - Technique

Biomechanics is perhaps the last area in the sport of rowing where meaningful gains can be made in speed. Rowing biomechanics is simply the study of rowing "technique". Just as engineers are applied scientists, rowing coaches of necessity must become applied biomechanics technicians. For the coach to reach his full potential as a rowing biomechanics expert he needs a tool that helps him show the athlete what is happening both kinematically and dynamically during the stroke by graphically describing the physical properties of Force, Acceleration and Velocity. Once the coach has the tool he needs to know how it works, how to use it, and how to decipher the reams of data that it produces.

Finding the Optimum Stroke

Over the last 30 years the physiological training limits for the rower have been tested just as it has in track and field, swimming and other endurance sports. Boat hull design has been explored and little probably can be done there to achieve increased measurable efficiency. Oar design, and rigging could still be maximized perhaps, but measuring potential improvements remains elusive. Finding the most efficient or optimum stroke looks to be the area where the most potential speed gains could come.

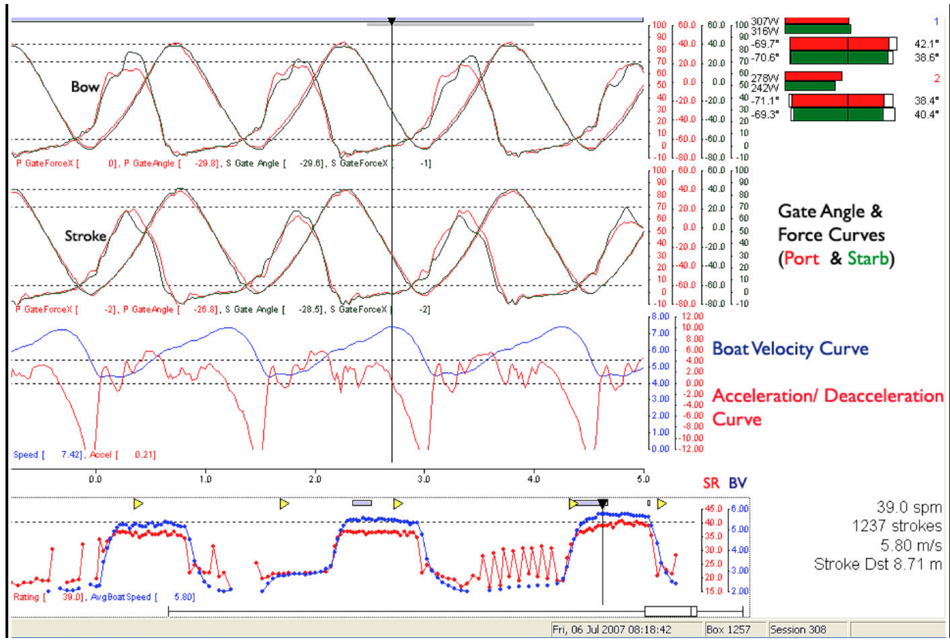
To find that elusive optimum stroke we must go beyond the coaches "eye" even if it is enhanced with a video camera. The body movements occur so fast during the drive that static analysis can lead to varying conclusions as to what is the best sequence of motions and where the emphasis should be. Dynamic analysis needs to be done by measuring and displaying the magnitude, shape, coincidence, and rate of change of the forces that occur when racing. That is what a Force Measurement System does.

Force measurement system hardware – the coach's tool

The heart of the force measurement system is the data logger. It is an electronic device attached to the boat which records for later playback the force applied to the oarlock pin, the angle of the oar, the boat speed and the boat acceleration. It receives its information on the force and the gate angle from a transducer located in a special pin that replaces the pin holding the oarlock. The accelerometer located at the keel picks up a signal from a NK impeller located under it on the outside of the hull. The accelerometer gives the boat velocity, and acceleration information. With the help of an algorithm in the software using the data from the pin transducers, it displays a handle speed curve after down loading to a computer. The only "real time" functions available to the rower while in the boat are the same as available in any NK Speed Coach – time, stroke rate, speed, and number of strokes. Both the transducers and accelerometers are connected to the data logger through cables and junction boxes in series; sort of like you would string Christmas tree lights. The data logger can be synchronized with a video camera in the coach boat so that the stroke can be displayed along with the curves and data. The data logger is taken from the coach boat after each outing and attached to a computer.

All this raw data is then available to display a variety of reports such as force, acceleration and velocity curves, handle speed curves, gate angle, power, oar slip, stopwatch, stroke and speed. The information that is downloaded after the rowing session can be used to make video comparisons shown side by side with the stroke curves for each individual stroke. This becomes a very powerful tool for individual feedback on the cause and affect of rowing technique differences. With the video image side by side on the same screen with the individual force curve and different individuals force curves from the boat we get to see how this "rowing mechanism" made up of different individuals and individual movements either contribute or detract from being an effective transmitted force.

Curves- what information is displayed



Once the information is downloaded from the data logger and the software does its work we get a trace report. This is where the fun begins. Your first reaction is usually: What is all this –big curves, little curves, four different color curves, numbers, bar charts, etc? The eye does not know quite where to focus. Usually it focuses on the “big mountains” first. This curve is the gate angle. The gate angle curve serves as a reference point for all the other curves and if a straight vertical line is drawn from any point on the gate angle curve down through the other curves you can see exactly where in the stroke sequence you are. The actual gate angle in degrees for the exact point in the stroke is printed under the curve. The second column of numbers to the right of the curve is the gate angle. So if the top of the curve corresponds with 40° that is the furthest the gate travels at the finish of the stroke. If the bottom of the curve corresponds with -70° than the total travel of the gate is 110°.

The force curve is the smaller ”hill”. The first column shows force in Newtons. If sculling - two curves show. One curve red and one green. It shows slight differences between port and starboard. If they were grossly displaced then the pin transducer would have to be checked for movement and zeroed. The curve will usually show up to three slight transition points where the legs, back and arms blend more or less successfully.

The third staff down shows the boat velocity curve (blue), and the acceleration curve (red). The two vertical columns to the right show velocity (meters per second), and acceleration (meters per second squared).

The very bottom of the page shows average boat speed (blue) and stroke rate (red).

Force curve shapes – sequential and simultaneous, which is optimum?

The object of force measurement is efficiency - to determine the optimum movements of the oar handle from catch entry of the blade into the water to finish release of the blade from the water (Effective Transmitted Force.) An optimum stroke will show the smooth acceleration of the oar handle using an emphasis on leg power for the first phase of the drive and than back and arm speed emphasis for the last part of the drive phase.

The force curve shown in the rowers report software show all the force curve traces for the outing. It looks like a bowl of pasta, but there is a distinct repeatable shape. This individual shape is the rowers "signature" and identifies how the force of the rower is applied during the stroke cycle and can be roughly sorted into sequential or simultaneous styles. A sequential rower (85% of all rowers according to Kleshnev) will use legs than the back and then the arms. A simultaneous rower (15%) will use a little of each. Sequential is more characteristic of sweep rowers, the faster boats and those with long legs. Simultaneous is more characteristic of scullers (particularly single scullers), those with long arms, broad shoulders and lightweight. Although this individual signature can be changed over time (usually with great difficulty), when coaching more than one rower per boat it is easier to start with a group that rows with a similar force curve shape and then attempt to refine the minor discrepancies. Which shape is best? The answer would be simultaneous if the rower were a machine because that shape is closer to square. However the prime mover –the rower in this biomechanical system is human and the kinematic links in this system (arms and legs and torso) are variable in length and vary from rower to rower.

When do we measure force – low stroke rate or high?

We always focus on short racing tempo pieces because this exaggerates the efficiency or inefficiency of the stroke. Rowing at 18 strokes per minute (training mode) and 35 spm (race pace) are like two different sports. The curves are quite different between training and racing rates. Basically the high rate measurements more clearly show discrepancies between the blending of the legs, back and arms during the drive and the effect of the 6 to 1 ratio of rower mass to boat mass is more clearly defined on the recovery.

Force, acceleration, velocity and handle speed models - mimicking the best rowers

Using the generated data from various sessions, with the assistance of basic physics and biomechanics principles the force, boat velocity, handle velocity, and boat acceleration curves are compared to published curves from the best medal wining boats. Basic physics confirm why certain shapes are good models for an efficient stroke. Published force, acceleration and speed curve data gathered from top crews point to the characteristic of an efficient stroke as having a front loaded first part of the drive with a long reach at the catch. Front loaded drive force is more efficient and results in more work energy and a more even power distribution. Stroke length and velocity of force application is of key importance.

Ideal Stroke Characteristics – what the curves tell us: "reading the tea leaves"

The Optimum Drive – What does it look like?

1. A quick catch is typical of a vertical placement of the blade and is shown on the handle speed curve, also as a steep initial slope of the force curve, a vertical acceleration curve, and flat to slight upward slope velocity curve.

2. As soon as the blade is buried an immediate push with the legs to accelerate the rowers mass and accumulate kinetic energy is shown by the steep, smooth initial slope of the force curve with a first peak, slight trough, also by the continued upward slope of the acceleration curve, and the increasing slope of the velocity curve

3. A smooth sequential blending of first the back and then the arm pull to continue building momentum of the system mass of rower and boat is shown by a rounded bulge or flat top and steep slope down for the force curve, a decreasing to zero acceleration curve, and an slight upward slope velocity curve.

The Optimum Recovery:

4. Since there is of course no positive force available during the recovery the focus must be on conservation of momentum and use of kinetic energy just before the catch. - The force curve is flat (no force) until just before the catch. With an increasing slope to maximum velocity, the boat achieves its maximum speed just before the catch. Zero acceleration is the case until just before the catch when a slight pull on the foot stretcher increases the boat speed and acceleration nears maximum just before maximum deceleration when the force on the foot stretcher starts to increase at the start of the catch. The handle speed curve is a “mirror” of the drive with less, slope after the release and more near the catch.

Force Curve Slope-Velocity

When interpreting data from force curves the slope of the force curve indicates how quickly the force increases by means of a fast leg drive and a seamless connection with the back. The slope of the force curve is the velocity of the force (not the boat

The shape of the force curve is important for synergism, but more important are the catch timing, initial slope and peak force matching. The more of these parameters you have trending in the same direction the more potential speed the combination will have. A steep slope is best and a matching slope and starting point is essential for synergism for any boat with more than one person. The way to achieve this steep slope curve is to have a fast approach to the catch only during the last third of the recovery resulting in a quick vertical catch instantaneously followed by a strong push with the legs to accelerate the rowers mass. This has many similarities to a “jump”, so that a 2000-meter rowing race can be described as 220 jumps.

Boat Acceleration Curve

The boat acceleration curves (red) have a characteristic “square root sign” with a deep negative peak just before the catch and a quick steep increase right after. The deceleration time is short but deep. There is a first positive peak right after the catch and then a slight decrease, which should not go negative. There is a second positive acceleration peak when the legs have stopped accelerating the rower's mass and the arms start to break. The longer this peak acceleration can be maintained the better.

Boat Velocity Curve

The boat velocity curve (blue) stays flat or slopes upward for the first part of the drive until the legs are almost down. From the 90-degree position until the finish the boat velocity increases and the velocity reaches its first peak during the later stages of the arm pull. The velocity of the boat continues to increase once the oars are out of the water until the pressure becomes positive on the footboard again and the rower's mass starts to decelerate just before the catch.

Oar handle speed curve

The handle speed curve is perhaps the most telling curve of all because it is a direct indication of effective transmitted force. The curve is derived as an algorism that integrates the gate angle form the pin transducer and the speed from the accelerometer. The curve mimics the form of a "little fish" and plots handle speed vs. gate angle. The initial plot is almost vertical indicating a quick catch, and then dips down as the blade is anchored in the water. Next, a steep slope shows good handle acceleration and then constant velocity until the release. The recovery mimics the drive with faster hands away than slowing with the body movement than faster again with the body movement just before the catch. The handle speed is the result of the interaction of all the body components – not just the arms. It explains why most scullers are simultaneous some very fast scullers row with what some would call obvious bad technique.

Basic Physics Concepts

To better understand and appreciate the curves and what they show about the rowing stroke it would be ideal if both the coach and the rower understood the basic physics concepts of **force, mass, acceleration, velocity, work, power, kinetic energy, momentum and impulse** This likelihood of this happening is probably never except perhaps at MIT or other engineering schools that have a rowing program. I recommend reading Part II, which is on our web site (technical papers) for a more detailed definition of basic physics as it relates to rowing. Much of the information that results from force measurement research is known intuitively by the best rowers and coaches. Force measurement curves just confirm the existing knowledge and point out areas to focus on when instructing rowing technique. However it also points out some misconceptions about the rowing stroke that have been promoted for a long time.

Classic misconceptions about the rowing stroke and what the curves show us

1. The peak force, and therefore the maximum emphasis is when the oar is perpendicular to the boat. -wrong
2. Row the blade in at the catch to get back splash, or hit the catch to get front splash. _Wrong
3. Slow the slide and the hands as you approach the front stops on the recovery. -Wrong

4. Pull hard at the catch to create a big puddle, or – ease it in at the catch –both Wrong
5. At the start drive half slide with the first stroke. -Wrong
6. Don't break the arms –maybe Wrong

Summation of rowing technique based on force measurement data

Each individual executes the drive portion of the stroke slightly different depending on body type and other factors, but in a crew boat all should strive to execute the most efficient or optimum stroke. The optimum stroke has an emphasis on leg push for the first part of the drive and an emphasis on arm pull for the last part. Handle speed is the major focus along with length.

A description of the most efficient stroke is a sequential involvement of first legs, then back, then arms with a focus first on leg velocity to accelerate the rower and then arm velocity to accelerate the rower plus boat combination. This recommendation is based on observations of the best rowers and physics.

The total drive takes place so quickly that it is impossible to focus on what is happening, so we rely on general physics principles, which the brain can instinctually execute. Three things have to happen with each and every stroke: A quick, vertical anchoring of the blade, immediately followed by an impulse force from the legs pushing on the foot stretcher to accelerate your mass and accumulate kinetic energy followed by a smooth transition swing using the momentum of the back and then the fast pull of the arms to continue the accumulation of kinetic energy, momentum and velocity of the system mass.

Understanding the information from the force measurement curves athletes can reinforce coaching instruction, and measure progress in mastering technique and synergism. Self-coaching is possible if the physics of the rowing stroke is understood. The data generated can be invaluable in quickly developing efficient technique, synchronization and ultimately making a fast boat at any level of competition.

FORCE MEASUREMENT: BACKGROUND INFORMATION

PART II – By Jim Dreher

A. OFF-WATER TRAINING

Off Water Simulation

On the land a template curve feature can be seen using a sliding head rowing simulator . This is not quite as pure as rowing the boat because it does not include the oar handling motions and the acceleration and speed variances of the boat, but the rowing simulator isolates the major pulling motion, duplicates the leg speed closely during the first part of the drive and since the moving head matches the acceleration of the boat closely at race pace it has about 80% similarity to on-water rowing.

The moving head of the simulator accurately simulates the negative acceleration of the boat at the catch but during the recovery the moving head accelerates faster than the boat, and the handle force is higher. This leads to inevitable differences in "boat feel" between boat and erg during the last part of the drive and the recovery. A major benefit of the rowing simulator is being able to have physically linked simulators side by side for rower synchronization while generating force curves on individual monitors. By matching the start of the force application, the rate of application (slope of the curve), and the peak force timing effective synergism can be trained for the first part of the drive.

B. ROWING PHYSICS

Rowing physics and biomechanics using a rowing information system

Being overly technical about what we are actually doing with regard to force, mass, energy, power, momentum, impulse, inertia and other Newtonian physics principals will not in itself make us faster rowers. However if we understand a few key concepts and focus on maximizing those physical principals that actually make us row faster, then understanding what is going on in regard to physics can be beneficial for mastering an efficient stroke by understanding what the force, acceleration, velocity and handle speed curves show us.

For the most part all technique coaching that rowers receive has been intuitively learned by the coach through experience and observation and then transmitted to the rower. The rower's execution of the described techniques are interpreted and based on his bias based on prior experience and observation. However rowing technique is applied biomechanics, it is not "faith" and smart rowers beyond the novice level find it difficult to accept technique principles based on faith in the coaches expertise. The rowing technique described by the coach has to have a sound, easily understood scientific explanation. Video analysis helps this interpretation process, but it is geometrical and only deals with the static frame by frame analysis of the body motion - the kinematics, or study of motion without regard to the forces involved. The coach and athlete can only guess, again based on experience where to put the emphasis and which sequence of movements is most economical with regard to magnitude and rate. The best coaches and athletes intuitively guess correctly most of the time, however to row with the most efficient technique (which is necessary at the highest levels of competition), the dynamics, or the study of the forces and their rate of application during the rowing stroke is essential. The FM data logger allows us to record and then analyze the force dynamics (force, acceleration, velocity and handle speed) curves in our quest for the most efficient stroke.

The forces involved in the rowing motion and the description of their magnitude, velocity, rate of change, their sequence and interrelationship (how the arms, back, and legs are used together) is what we study when we consider the "technique" or biomechanics of the rowing stroke.

1. FORCE

The primitive definition of force is a push or pull exerted by our muscles. When we row we change the velocity of the oar, boat and ourselves as we pull the handle and push on the foot stretcher. The result of this pushing and pulling is a change in velocity or an acceleration of the mass of the system, which is the sum of the individual masses of boat, oars and rower. This is the fundamental equation of classical mechanics, Newton's second law: force = mass x acceleration, or **F = M x A**. This is what we do each and every time we take a stroke. We apply a force; accelerate our mass, and the boats mass. In the boat the FM data logger records this information and after the on-the-water session we play it back. The software converts the force information to numerical and graphical form so we can analyze it.

2. WORK

For analyses purposes we need a few other definitions. One is the definition of work. **Work =force x distance** and the units we use for work is the Joule, Newton for the force and meter for the distance, so: Joule = Newton x meter. When you do work you gain energy, measured in Joules. If you apply a force (Newton's), through a distance (meters) you do work (gain energy) measured in Joules. This is what you see in the first stave of the trace view. This is effective gate force (force applied to the oarlock pin, resolved in the direction of boat travel) over time. The area under the curve can be considered work energy.

3. POWER

Power is the rate that work is being done. As rowers we are more interested in power than work. The unit of power is the Watt**. Watt = Joule divided by time**. The FM software calculates the power in Watts and displays it in the upper right hand margin of the trace view.

4. KINETIC ENERGY

In the trace view on the last stave the red acceleration curve for the boat during the last part of the recovery and the first part of the drive we can see a rapid deceleration and then a quick acceleration. This is a result of our mass which is about 6 times the mass of the boat, effectively decoupled from the boats mass and rapidly changing its velocity (decelerating and then accelerating). This energy done by us to accelerate and decelerate our mass is referred to as kinetic energy and is one half the mass times the velocity squared. **$KE=1/2MV^2$ Kinetic energy is just our ability to do work by virtue of our motion. The work energy we do in moving our mass is always equal to the change in kinetic energy.**

When you do work (force through distance) you increase kinetic energy. On the drive when you push on the foot stretcher and pull on the oar handle you (your mass) is accelerated, travels 60 cm up the slide and gains kinetic energy. Once you gain kinetic energy by using your legs then your mass and the boats mass becomes one (a system mass). For the rest of the drive you are using first the back and then the arms to continue the acceleration of the system mass of boat and rower and continue to gain kinetic energy. The kinetic energy that you have gained with the legs helps the back swing by itself (momentum) and initially helps the weaker arms continue the acceleration of the handle.

5. MOMENTUM and IMPULSE

The swing of the upper body (where your center of mass is located) with out any effort on your part is an illustration of momentum. Momentum equals Mass times Velocity, **$\rho = M \times V$**. The acceleration curve has a first peak, which is almost completely due to leg drive accelerating the complete body mass and gaining kinetic energy. The second peak is primarily due to upper body mass swing momentum and arm velocity gaining even more kinetic energy. Another way to state **Newton's 2^{nd} law is: the rate of change of momentum x velocity= force x time.**

If the force is very high and the time very short than the change in momentum is an impulse type of force. During the second part of the drive the rate of change of momentum is slower, but speeding it up will increase acceleration and increase kinetic energy.

By looking at the force curves that we generate using the data logger we can see how to effectively use our power application to our advantage. The area under the force curve could be a change in kinetic energy if we think of force over distance or a change in momentum if we think of it as force over time, and impulse if a very quick catch and high force application (steep slope on the force curve).

The equation for work energy: **$W = F \times d$** is intuitive and shows that no mater how high the force, no work can be done unless there is movement, a force through a distance. Because of the high load at full reach at the catch if we try to pull and simultaneously place the blade in the water we will either do an isometric exercise (no work done because no movement) or we will have to start to pull before the blade is fully buried and get little or negative forward progress because the blade is slipping at the catch. However an impulse force is typical of the catch. This apparent contradiction illustrates that the catch has to be quick to get the blade anchored in the water, but it is nonproductive to exert a high force. That is why we say: "catch than drive". This is how to use the physics of rowing to legitimize the arguments for not pulling until the oar is placed and fully submerged at the catch. The equation for work can also be used to show that perhaps more efficient work can be done by a long stroke with a lesser force than by a high force over a short distance.

C. ROWING TECHNIQUE

1. Observations on efficient stroke technique based on a published data base:

Over about 7 years Dr. Valery Kleshnev has built a data base of over 7000 individual rowing data entries with various level crews, both sweep and sculling all using a FM system. He continues to publish his Rowing Biomechanics Newsletter monthly and it is an invaluable source of rowing biomechanics information. His observations of the force curves of the best rowers and how they achieve a more efficient technique is the basis for the analysis of our own data.

2. The 3 Basic Tenets of the Optimum Stroke

The key observation from Kleshnev's data is how the best rowers first accelerate their mass with the legs during the first phase of the drive and then using arm speed to accelerate the combination mass of the rower and the boat during the second half of the drive. His data show the various force, acceleration and speed curve data characteristics of fast crews. Based on his observations the basic tenets of the optimum stroke are:

a.) A long stroke starting with a quick, vertical placement of the blade.
b.) An immediate explosive push with the legs to about 70% of maximum power to accelerate the rowers mass while the arms are "hanging".
c.) As the legs come down a smooth sequential blending of the back and then a fast arm pull to continue the acceleration of the system mass.

His data show that if we want to row like the best rowers in the world we should first push with the legs to accelerate our center of mass as quickly as possible and then continue the acceleration of both our mass and the boats mass together as long as possible by pulling with the arms.

3. Two Rowing Styles Predominate – Sequential and Simultaneous

Two major classifications of rowers: Sequential or Simultaneous involvement of the legs, back and arms were shown by his data.

a.) Sequential involvement of first legs, then back and arms (classical style) has a higher maximum force and power and results in a triangular shaped force curve and is typical of 80-85% of rowers in his data bank.
b.) The simultaneous work of legs and trunk style of rowing results in a more rectangular shape of the power curve, but with lower peak force and power for 15-20% of the rowers in his data bank.

We have found that this simultaneous style seems to be the most efficient but is more common with single scullers and those with broad shoulders with tip to tip of finger arm spread greater than their height.

On the average legs produce nearly half of the power but take up only about 35% of the drive length (arms contribute 37% of the stroke length in sculling)

Leg power increases to as much as 57% of the total power of the drive at high stroke rates (36-40). Arms have opposite trend.

Elite rowers have very high (1.5-1.6 m/s) max leg and trunk speed, and even higher arm speed -1.9 to 2.0 m/s.

The data shows an emphasis on leg power for the first part of the drive and an emphasis on arm speed for the last part. This leads to recommendations on rowing technique and on drills and specific exercises to train the different muscle groups used for the parts of the drive to maximize their contribution to boat speed. On the water drills focusing on the various elements of the stroke at the same velocity, but at reduced force or time will train "muscle memory" and allow rowers to focus on the training goal which is specific to the boat type over the Olympic distance. The force curve data suggests that off water strength training (cross training) should focus as close as possible on a replication of the rowing motion with regard to force level and velocity.

4. Kleshnev's Rowing Biomechanics data – Trampoline effect

To understand how to best apply force to maximize performance you first have to understand how you're mass moves in relation to the boats mass. Kleshnev references the "system" made up of the rower and the boat. It has a direct analogy in the solar system where the earth and the sun go around a common center of mass, but the position of the center of mass of the system is much closer to the sun because its mass is so much greater than the earth. So it is with the rower and the boat. The rower's mass is about 6 times the boats mass. When a 90 kg. rower moves in a 15 kg. boat a distance of 630 mm displacement of the rower's center of mass will be only 9 mm and the boat moves 540 mm.

Once we understand that we are dealing with two separate masses and that one has an affect that is 6 times the other we intuitively know that the average speed of the rower-boat system can be increased if we can just know how and when to accelerate (change the velocity) our mass.

The only time that the system can be accelerated is during the drive when the blade is locked in the water. The more acceleration of the system there is during this time, the higher the average speed. During the drive the system accumulates kinetic energy and then loses it during the recovery according to the formula $\mathbf{KE=1/2MV^2}$. During the recovery we conserve the kinetic energy we gained during the drive by a controlled recovery with the peak velocity close to the catch. This late peak of seat velocity also helps with a quicker catch and a faster drive (Kleshnev's trampoline effect).

The velocity of the rower's mass is the focus of the first part of the drive when both the force and acceleration curves have the steepest slopes and the boat is initially accelerated.

The equation for momentum $\boldsymbol{\rho = M \times V}$ and the equation for power $\mathbf{P = F \times V}$ all highlight the importance of velocity along with force to first accelerate the rowers mass and then the boat along with it.

As we increase the force and reduce the time we approach an impulsive type of force application. Impulse = Force x time**,** $\mathbf{I = F \times t}$.

Impulse is momentum change when the force is very high and the time is very short. An impulse type force curve slope becomes almost vertical. A typical example of impulse in the extreme is that of a baseball and bat colliding referred to as "Impact".

In rowing we are a long way from this analogy, however, during the last 30 years the drive force and velocity is trending in this direction and the consequences have implications for training and equipment.

As the catch gets quicker and the initial forces are applied faster and with a higher average and at a more extreme angle at the catch the load on the rowers muscles, bones, ligaments, tendons and cartilage increases. Too high a load, or repeated impact type loads can lead to injuries and over training. So we need to insert with a quick catch, and then an immediate application of force loads with high stroke rates in our general endurance training, but we have to make sure we limit the force levels and the duration to prevent potential injuries.

High rating pieces during endurance workouts should be limited to 45 seconds with at least 3 to 5 minutes recovery time between pieces. This is similar to what a hockey player on a team with four lines sees. This impulse trend has implications for equipment such as needing stiff riggers designed to resist the higher forces resulting from more acute catch angles.

This also is a recommendation for softer oars for training and stiffer for racing. Also oar blade area does not need to be as large with a long reach and a quick, deep placement so smaller blades and shorter outboard is recommended. The main message to take away from the discussion of rowing physics momentum and impact is this: If you want the boat to have high average velocity you must have acceleration, which increases velocity, which increases the kinetic energy and momentum. The faster you accelerate just prior to the catch the quicker you set the blade. The quicker the blade is set the faster you can push with the legs, swing the back and pull the arms. Everything starts with that last part of the recovery. This is the old coach's intuitive expression "the catch starts with the recovery" or what Kleshnev calls the trampoline effect.

D. OTHER

1. Training parameters

The goal of most competitive rowing is to be able to race the 2000-meter Olympic distance in the quickest possible time. To achieve that goal you need to be as fit as the competition and your rowing technique must be as efficient as possible in order to prevail.

As an example: In the men's open double at the Olympics if you can row about 225 strokes for about 6:10 under normal conditions of wind and water temperature, and it takes the boats racing against you a bit longer you will medal or win in 2012. All the participants in the A and B final will be virtually identical in training preparation and physiology. Victory will be possible only by the top 3 or 4 in the A and the top 2 in the B finals who make the stroke cycle as efficient as possible and are synergistically the most compatible. Their boat speed will be within 1% of each other.

All things being equal the competitor that has the combination of the longest stroke and the highest stroke rating which yields the maximum percent of the race time with the oar blade in the water at the maximum possible average power will win the race.

Note that this strategy or rowing theory is based on three principles:

a.) A long stroke.
b.) A high stroke rating.
c.) Maximum average force.

Assuming that you have the boat rigged correctly to achieve both length and high stroke rate, you must find the highest average power per stroke that you can sustain. It also requires learning how best to apply the force, the time and the rate of force application. This is the goal of endurance, speed and technique training. It requires much practice, thought and trial and error to find the most efficient "cruising speed".

2. Rowing with more than one person – synchronization

To coach more than one person per boat the major emphasis is on perfect synergy of the power application. Once there is more than one person in a boat technique differences have the detrimental effect of diminishing rather than reinforcing the potential net propulsion force. The main problem becomes one of synchronization of forces. Rowing becomes a kinematics and biomechanics choreography problem. Two or more rowers must apply the propelling force in exactly the same way in order to move the boat in an optimum way. The exception – the pair, proves the rule, since it is a "couple", and to go straight the stroke has to have a higher force at the catch. The problem is compounded because with the possible exception of identical twins different rowers with slightly different body types will apply the propelling forces in slightly different ways, ways that may be efficient for one but counteracting by two or more.

For the upper body - arms and torso this is somewhat easier to synchronize. However for the lower body – the legs, it is necessary that the length of the total of the upper and lower limbs is as close as possible when picking a potential crew. Pick the crew by the inseam if possible. Selecting a crew sculling boat requires finding athletes with the top physical parameters is relatively easy. Size, erg score, proficiency in the single are the obvious starting points. Not initially obvious are other more subtle physical characteristics such as shoulder width, arm and upper body length proportions. The most useful criteria from a geometrical or kinematics viewpoint is leg length and arm span versus height. If possible recruit by inseam, shoulder width and a total arm span greater than total height. It results in simultaneous power curves, long strokes and therefore makes matching the force curves easier.

Once you add one more person and create a double or pair it becomes almost a different sport. Now everything is about matching the application of power to move the boat efficiently. This is difficult to do without some outside aids.

Very good rowers can "feel" the matching of the power application in a double. It is almost impossible in larger boat classes. Even using slow motion video analysis as an aid has its limitations because we are viewing a kinematic or virtually static situation with out regard to the dynamics, or the forces that the movements generate. It is particularly difficult with rowers of different size with different body proportions who naturally use the legs, back and arms sequence at slightly different proportions and rates.

The best training aid for "crew" boats is the force measurement system to display the actual force, acceleration and velocity curve. Land based training using two or more moving head rowing simulators is the next best training aid because the physics duplicate the rowing action of "pulling the boat up under you" and displays a force curve which can be matched by all members of the crew. Even if the shape of each individual curve is not identical in amplitude, length, etc., if all the peaks of their individual power curves nest together and the slope of the curve is the same then the crew will have near identical power application.

3. Off water (cross training)

When training for rowing we first must consider the distance and average force and rating that the distance requires. Since most rowing involves the Olympic distance of 2000 meters and most crew boat classes will experience times of about 6 minutes plus or minus 30 seconds at 35 to 40 spm we must train our muscles to work efficiently at the rate and average force level to maintain that boat velocity. Since obviously we cannot do this for extended periods without causing far more harm than good we must vary the force, time, rate and recovery. This is the stuff of training that is not the focus of this explanation of force measurement dynamics. However when looking at the force dynamics we must mention that the average force level and rate that we race at must be reached a number of times during each workout so that our "muscle memory" is refreshed periodically. This is the focus of drills inserted during training sessions. Off water training has a parallel situation in that the movements and the rate of movements of alternative exercises should be similar to the rowing motion and rate of motion, or what is called "specificity of exercise". The moving head rowing simulator is more specific (80%) than a C2 ergometer (60%). A one-leg jump squat using the other leg for initial acceleration has a similar speed profile to the rowing stroke. A sit down rowing machine can be used for the placement drill motion, or even the C2 erg with the back raised on blocks can be used to train leg speed. If the alternative exercise is not specific in one area but complementary in another it can be useful. Cross country skiing or roller skiing with poles are excellent examples of alternative exercises similar to rowing.

4. A note on the C2 erg:

Kleshnev explain why some athletes perform well on the erg and less so by comparison on the water. In the boat, because the blade propulsive efficiency is highest at the catch, the foot stretcher force is 30% higher than handle force and subsequently the workload is higher on the legs and lower body. On the erg the arms and upper body are heavier loaded in comparison to the legs probably due to body mass momentum emphasis on the second half of the drive. Using the handle speed data for two actual athletes shows constant or decreasing handle velocity for the first 10° to 15° of gate angle. Leg force is the preferred force for handle acceleration in the first part of the drive. Back and arm force continues handle velocity in the second part of the drive. Since the erg favors those with a power emphasis toward the last part of the stroke results will be better for them. In the boat blade efficiency is highest in the first part of the drive and boat resistance is greater during the last part of the drive (power required=drag factor of hull x V^3) so you don't get a good return from your effort if it is focused on the last part of the stroke because you must pull increasingly hard to overcome boat resistance which is increasing with the cube of the speed. So a 6K or hour erg test will be a good indicator of endurance level conditioning but it may have a negative correlation to what is effective technique on the water.

All ergs are cross training devices and don't exactly simulate the rowing motion. According to Kleshnev the C2 overall is estimated to be only about a 60% simulation to on the water rowing. The dynamic erg is a little better, estimated to be about 80% overall, and has a very close replication of the negative acceleration of the boat at the catch and a close approximation of the entire boat acceleration curve at racing pace.

Kleshnev's force measurement data shows: In the boat footboard force develops earlier and is 30% higher than handle force. On the erg higher inertia forces are needed to overcome a mass change of direction six times that experienced in the boat. Erg footboard and handle forces are about equal and handle force develops much later with a higher peak. Erg handle velocity increases slower and then remains constant. The boat is the opposite. Because of higher leg velocity and higher foot stretcher force on the water rowing has about 10% higher leg involvement and about 4% less back and arms than erg rowing. Because of this rowers with fast legs produce more power on the water. Rowers with slower legs and stronger upper body or proportionally more upper body involvement can have higher erg scores. Rowers with long legs could have a compounded advantage on the erg because the erg allows as much as a 5% longer stroke compared to the boat with about a 10% longer leg drive due to more compression at the catch due to mass inertia. So the legs can generate more work on the erg but at a slower rate. On the water the legs work quicker at the catch, but at a lower force level.

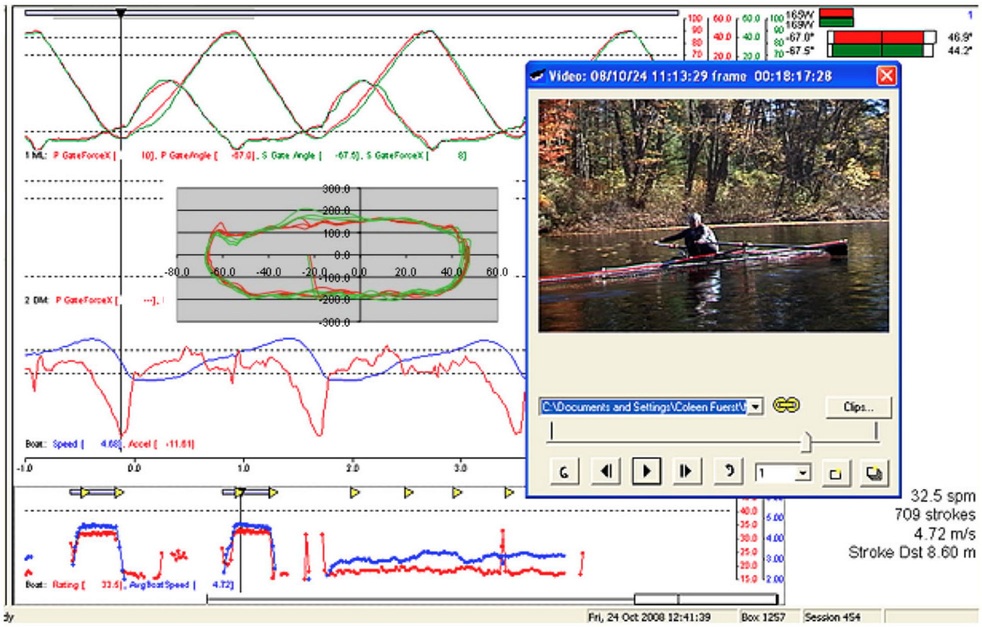
If we accept the handle speed data for the two actual athletes and attempt to proscribe a "fix" for this slowing of the handle due to slow leg speed perhaps on the water drills such as what I call "punching" or placement drill with no back swing at a high rate and low force or off the water cleans with low weight will focus on the initial drive by relying on the legs and hanging with the arms to achieve initial handle acceleration.

5. Four Reports of Single Sculls:

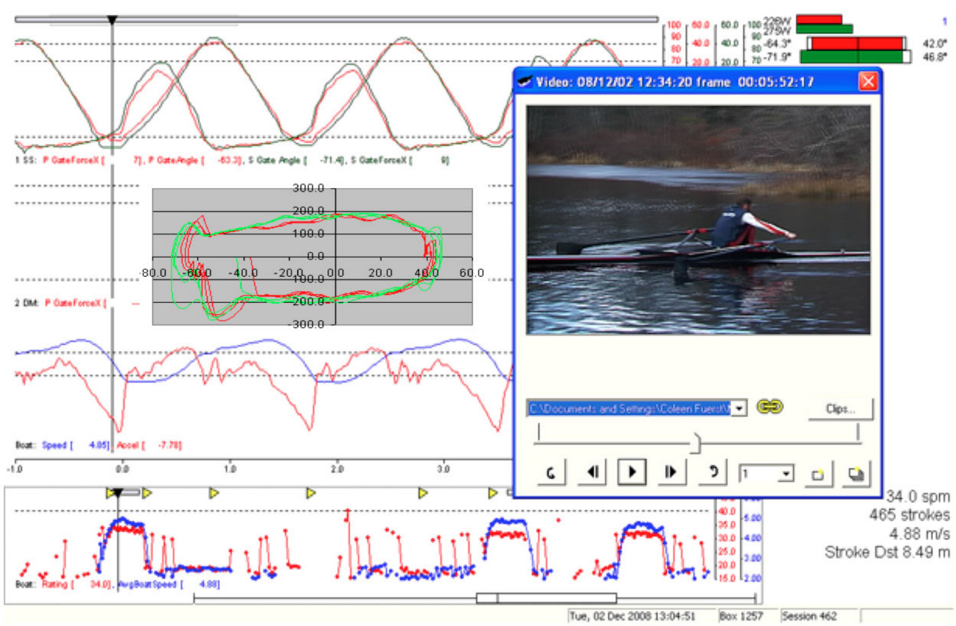
These following reports (with the embedded handle speed curves from page 4) are screen shots of four world-class scullers collected with an early version of the Peach System. The handle speed curve for each was extracted from the same 4 strokes of data and inserted later. Now with our Indoor Rowing Tank Adapted System we are able to see on the same screen the handle speed curve in real-time just below the Force Curve.

The Elite LM 1X Momentum and Handle Speed Curves (last of four curves on page 40) show the greatest handle acceleration, quickest catches, and best conservation of momentum just prior to the catch we have seen, all of which makes it a very good model to emulate.

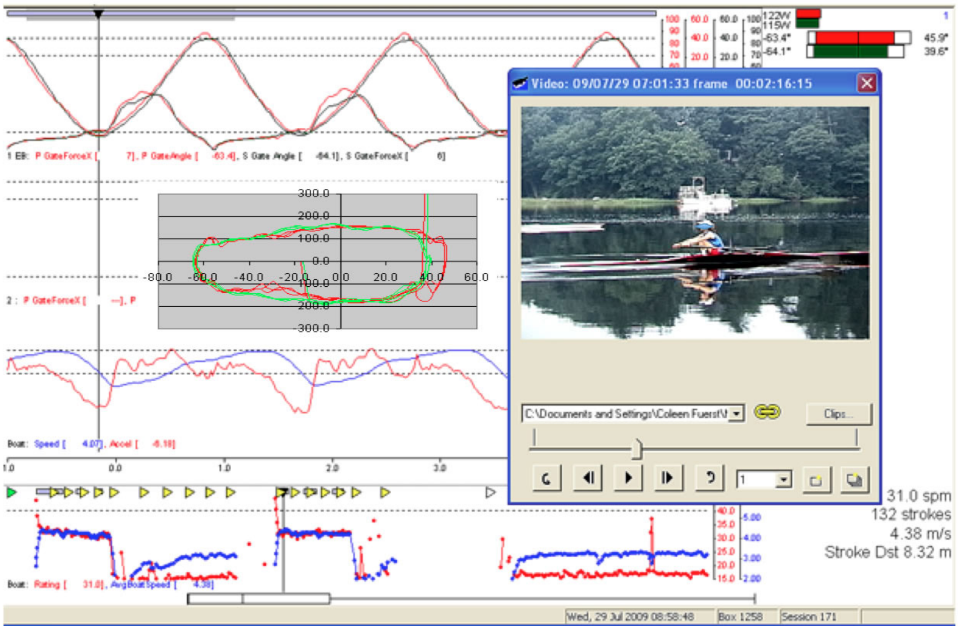
Elite HWW Curves



Elite HWM 1X Curves



U23 LWW Curves



Elite LM 1X Curves