# Effects of Various Inefficiencies in Rowing on Shell Speed

by

Stephen F. Young, Jr

Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of

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## ABSTRACT

First order predictions were made in determining the effects of various sources of inefficiency in rowing on shell speed. These predictions were then tested using a MATLAB model of the rowing stroke. The model simulates an eight man oared rowing shell and determines average shell speed, stroke rating, power per stroke, and time over a 2000 meter race. Several parameters of the rowing model are manipulated to determine the effects of each source of inefficiency on shell speed. Of the sources tested, three can be attributed to the shell manufacturer, and the others can be attributed to the rowers themselves.

The sources of inefficiency tested are wetted surface area, coefficient of friction, dynamic and static weight, stroke length, slide acceleration, and stroke rating. The effects on shell velocity were normalized to determine which sources resulted in the greatest inefficiencies. The ranking of sources from greatest to smallest effect on shell speed are stroke rating, coefficient of friction, wetted surface area, stroke length, static weight, dynamic weight, and slide acceleration.

Thesis Supervisor: Michael S. Triantafyllou
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## INTRODUCTION

Rowing coaches, athletes, and boat manufacturers have competing theories about which factors contribute most to a boat's speed through the water. The main rowing shell properties believed to have the greatest effect on shell speed are wetted surface area, shell stiffness, bow shape, and weight. There are also several factors related to technique that are believed to have equal or greater effects on shell speed such as catch and finish angle, recovery speed, stroke rating, and power application through the drive. The effects of these various factors can only be truly understood with an accurate model of the rowing stroke. The two parts of the rowing cycle are the drive and the recovery. Since rowing does not supply a continuous source of propulsion, the shell responds differently than typical ships.

The primary task was to make first order predictions about several sources of inefficiency on shell speed. These predictions were then compared to a computer model of the rowing cycle which accounts for the velocity fluctuations during the rowing cycle. The model uses MATLAB and is adapted from Marinus van Holst's Simulation of Rowing, which was originally designed to model a heavyweight single scull. The model was altered to simulate a heavyweight men's eight man shell and to reflect a more accurate recovery profile. The main interactions to consider in the model are blade to water, handle to rower, rower to shell, and shell to water. Each interaction was combined in a Simulink model that calculates the shell speed throughout the stroke cycle. The model also determines several points of interest including stroke rating, rower power, and time over a 2000 meter course which is the standard length race in collegiate, club, and international rowing.

The objective was to determine which factors are responsible for the greatest speed fluctuations. This information will be used to enable boat manufacturers and coaches to reduce the main sources of inefficiency in rowing. The model considered three manufacturer and three rower sources of inefficiency. The factors were manipulated in the Simulink model and the results were normalized to compare the effects of the various sources of inefficiency. The results are then analyzed to determine realistically which factors have the greatest effect on shell speed.

## BACKGROUND

The sport of rowing began hundreds of years ago and debuted as an Olympic sport in Paris in 1900. There have been several advancements in both equipment and rowing technique over the past few decades, the most significant being the introduction of carbon fiber to shell and oar construction. There are several questions around the rowing league that still remain unanswered regarding the properties of both shell and technique with respect to their effects on hull speed. Since its inception, engineers have been trying to build the fastest boats possible, and coaches have been trying to teach the most efficient stroke possible. Building the fastest shell and coaching the most efficient stroke are only possible after the effects of various factors on shell speed are determined.

In order to understand the rowing model used, it is important to have a general knowledge of the rowing cycle. The two phases of the rowing stroke are the drive and the recovery. The drive is the power application phase where the rower transfers force to the blade through the oar handle, accelerating the shell. The power supplied by the rowers comes from the legs, bodies, and arms with the majority of the power being generated by the legs. During the recovery, the blade is completely out of the water and the rower transfers his body weight towards the stern of the boat using a sliding seat. In this phase, the shell is decelerating due to the frictional force between the shell and the water.

The two main power applications taught are increasing force on the handle through the drive and supplying a constant force to the handle during the drive which results in a parabolic power curve. The model assumes a parabolic blade force that reflects the second method of supplying a constant force to the handle during the drive. This method is most commonly seen in heavyweight rowing, whereas the method of building force through the drive is more commonly seen in lightweight rowing.

## MODEL

The model of the rowing stroke was created using MATLAB and Simulink. The simulation generated results that correspond to an elite club or collegiate men's heavyweight 8+ with a crew average of 205 lbs. The base figures such as catch and finish angle, blade force, and power per stroke were taken from experimental data for heavyweight sweep rowing. Other parameters such as coefficient of friction, wetted surface area, and weight were taken from boat manufacturers' specification sheets or calculated directly.

The Simulink model uses the MATLAB ode45 differential equation solver to determine instantaneous information about the system such as shell speed, shell position, oar angle, and rower power. The model begins in the drive phase and continues to run until a steady state speed is reached. The model accuracy is determined by the step size which is defined by the user in the shell.m file.

The model receives shell parameters defined by the user such as shell weight, rower weight, maximum blade force, and recovery time. The values generated by the Simulink model are stored in arrays and accessed by results.m which calculates the desired outputs. The main output of interest is the average velocity of the shell which is calculated by determining the distance traveled by the shell during one stroke cycle and dividing that distance by the time it takes to complete one stroke.

The other outputs of importance are stroke rating, rower power, and the time it takes to complete a 2000 meter race. The stroke rating is determined partially by the user input of recovery time and the also by the drive time which is determined by the model. The importance of this is that the predictions were made by assuming a constant stroke rating while the other parameters are changed. The rower power, which is determined by the model, is checked against empirical data to be sure the Simulink model is accurate. Finally, the time it takes to cover a 2000 meter course is calculated in order to determine exactly how many seconds are saved by increasing the efficiency of each parameter.

Rowing can be modeled by combining the four interactions of blade to water, handle to rower, rower to shell, and shell to water. Each interaction is described in more detail below. The first interaction to consider is the interaction between the blade and the water. The blade is foil-shaped and therefore has a drag force and a lift force associated with it as it is pulled through the water. The instantaneous force on the blade is determined by generating a parabolic curve from the initial, maximum, and final blade forces. For the purpose of the model, the forces on the blade at the catch and release are equal to zero, and the maximum force on the blade occurs when the oar is roughly halfway between the catch and release angle. The blade is also represented as a flat plate and the surface area of the blade is slightly overestimated to account for the increased force on the surface of the blade due to its geometry.

The two forces on the blade vary through the course of the stroke as the blade changes orientation with respect to the shell. The coefficient of lift and drag also changes as the angle of attack changes through the drive. The following plot shows the coefficients of drag and lift with respect to attack angle. The maximum values of the lift and drag coefficients occur at an attack angle of $\pi/4$ and $\pi/2$ radians, respectively.

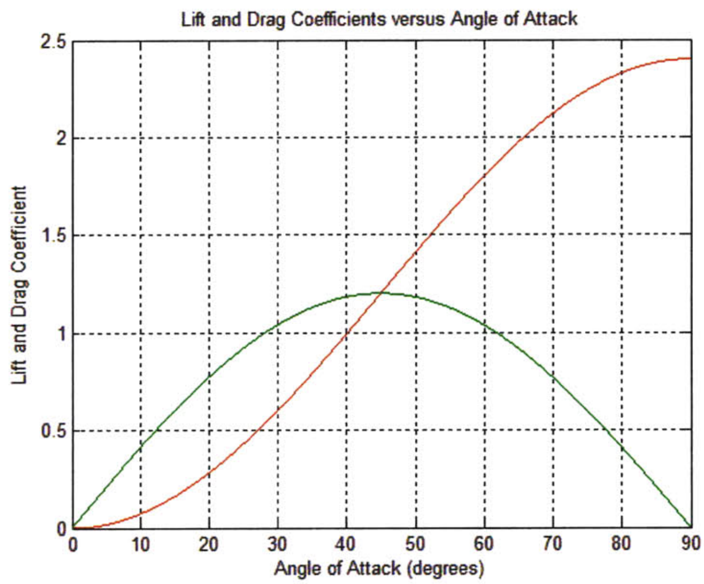


Figure 1: Lift and drag coefficients versus blade angle of attack

In figure 1, the green curve corresponds to the lift coefficient and the red curve corresponds to the drag coefficient. The total blade force is found by taking the sum of the lift and drag forces on the blade. The lift and drag forces on the blade can be found using the standard drag equation.

$$F_d = \tfrac{1}{2}\rho u^2 A C_d \tag{1}$$

$$F_l = \tfrac{1}{2}\rho u^2 A C_l \tag{2}$$

In equations 1 and 2, $\rho$ is the density of water, u is the blade velocity with respect to the water, and A is the surface area of the blade. An overhead view of the blade interaction with the water shows the relevant parameters of the model.

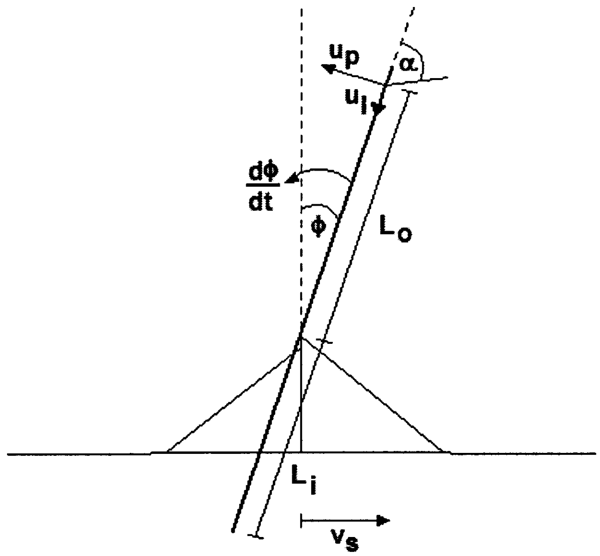

Figure 2: Overhead view of oar and shell

The blade velocity, u, is calculated by combining the perpendicular and lateral blade velocities, $u_p$ and $u_l$.

$$u = \sqrt{u_p^2 + u_l^2} \tag{3}$$

The blade force, $F_b$, is calculated by combining the lift and drag forces, $F_l$ and $F_d$, in the same manner.

$$F_b = \sqrt{F_l^2 + F_d^2} \tag{4}$$

Equation 4 can be expressed in terms of the drag and lift coefficients.

$$F_b = \tfrac{1}{2}\rho u^2 A \sqrt{C_d^2 + C_l^2} \tag{5}$$

The perpendicular and lateral blade velocities are expressed in terms of the angular velocity of the oar, the angle of the oar, and the shell velocity. The equations for $u_p$ and $u_l$ are used to determine the velocity of the shell over the total angle of the drive.

$$u_p = \frac{d\phi}{dt} L_o - v_s \cos\phi \tag{6}$$

$$u_l = v_s \sin\phi \tag{7}$$

In the equations for $u_p$ and $u_l$, $v_s$ is the velocity of the rowing shell, $\frac{d\phi}{dt}$ is the angular velocity of the oar, and $L_o$ is the outboard length of the oar measured from the center of effort of the blade to the oarlock. Since the blade does not stay fixed in the same position, relative to the water during the drive, the angular velocity cannot be equated directly to the shell velocity as it can in a no-slip condition.

The next interaction to consider is the interaction between the rower and the handle. The model calculates the force on the surface of the blade throughout the drive which can be used to calculate the force at the handle that resists the pull of the rower. This is calculated using the ratio of the inboard length of the oar to the outboard length of the oar.

This equation is not necessary for the model but it is used in determining the power output of each rower.

$$F_h = \frac{L_o}{L_i} F_b \tag{8}$$

In equation 8, the inboard length, $L_i$, is measured as the distance from the center of effort of the rower on the handle to the oarlock. The inboard length is roughly half of the outboard length and therefore the rower must generate a force that is at least twice the force on the blade in order to accelerate the shell through the water. The force applied to the oar handle by the rower is the result of the forces generated by the rower's legs, body, and arms.

$$F_{row} = F_{legs} + F_{body} + F_{arms} \tag{9}$$

The total force generated by the rower is distributed between the foot stretchers and the oar handle. The following interaction between the rower and the shell illustrates the distribution of forces more clearly and provides a model to explain the effect of the moving rower on the shell speed during the recovery.

The three points of contact for the rower are the foot stretchers, the seat, and the oar handle. Since the seat is on a rolling carriage, the center of mass of the entire system changes significantly throughout the rowing cycle. For the purpose of the model, the rolling friction of the seat is ignored since this force is trivial compared to the magnitudes of the other forces acting on the system. The acceleration of the rower with respect to the shell is derived by combining the forces acting on the handle and foot stretchers.

$$\frac{d^2y}{dt^2} = \frac{F_{ft} - F_h}{m_r} \tag{10}$$

The total force generated by the rower is an internal force and only the force applied to the foot stretchers will accelerate the rower. By using multiple reference frames, the equations of motion for the entire system can be expressed in terms of the acceleration of the rower's mass with respect to the shell.

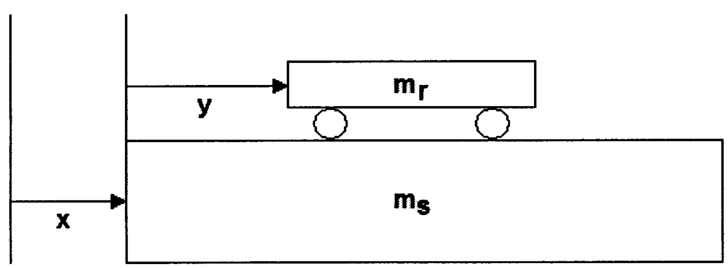


Figure 3: Model of Recovery

The relation between the three coordinates is expressed in equation 11.

$$z(m_s + m_r) = xm_s + (x + y)m_r \tag{11}$$

In equation 11, x is the absolute position of the shell, y is the relative position of the rower with respect to the shell, and z is the absolute position of the center of mass of the system. Using simple algebra, equation 11 can be used to solve for z in terms of x, y, the shell mass, $m_s$, and the rower's mass, $m_r$.

$$z = x + \frac{m_r}{m_s + m_r} y \tag{12}$$

The equation of motion for the system can be expressed in the following manner:

$$F_{ext} = (m_s + m_r) \frac{d^2 z}{dt^2} \tag{13}$$

By substituting x for z, the equation of motion can be expressed purely in terms of x, y, $m_s$, $m_r$, and the external forces on the shell, $F_{ext}$.

$$F_{ext} = (m_s + m_r)(\frac{d^2 x}{dt^2} + \frac{m_r}{m_s + m_r} \frac{d^2 y}{dt^2}) \tag{14}$$

The external force on the shell leads us to our final interaction between the shell and the water. The model assumes that the only external forces acting on the shell are drag forces due to the water/shell interaction. This means that the model is designed to only consider a case in which there is no wind or waves which would add other external forces to the equation.

The total resistance on the shell is due to the friction drag on the shell, and the wave-making drag. The friction drag on a shell is explicitly defined; however, the wave-making drag depends heavily on shell geometry and can only be determined using empirical formulas that have been fit to data. For this reason, the wave-making drag is absorbed into the coefficient of friction used to determine the friction drag on the shell.

$$R_f = C_f \tfrac{1}{2} \rho v_s^2 S \tag{15}$$

For the purpose of the model, ρ does not change and $C_f$ absorbs the factor of $\frac{1}{2}$ and the density of water to become $C_{tot}$. The external force on the shell is equal to the total resistance on the shell.

$$F_{ext} = R_{tot} = C_{tot} v_s^2 S \tag{16}$$

Substituting equation 16 into 14, the acceleration of the shell can be expressed in terms of known masses and forces on the shell.

$$a_s = - \frac{m_r}{m_s + m_r} \frac{d^2 y}{dt^2} - \frac{C_{tot} S}{m_s + m_r} v_s^2 \tag{17}$$

Equation 17 is the main equation used by the MATLAB model to determine the instantaneous shell velocity. The model also uses equations 5, 6, and 7 to determine the shell velocity during the drive. The force on the surface of the blade is defined by the parabolic force curve generated by the shell.m file. The model then determines the perpendicular and lateral blade velocities that correspond to the known blade force. The shell velocity is then calculated using equations 6 and 7 for a known blade force and oar angle.

## PREDICTIONS

The sources of inefficiency considered in this study are wetted surface area, coefficient of friction, static weight, dynamic weight, stroke length, stroke rating, and slide acceleration. Of these, the first three are properties of the rowing shell and the rest can be attributed to the rowers and their technique. The sources of inefficiency will be normalized in order to determine which sources have the greatest effect on shell velocity.

The first sources of inefficiency to consider are wetted surface area and coefficient of friction. From equations 15 and 16, it is clear that the frictional and total resistance increase linearly with respect to both the wetted surface area and the coefficient of friction. We can determine the power required to attain a specific speed using equation 16.

$$P = C_{tot} v_s^{\,3} S \tag{18}$$

Assuming constant power, i.e. the same rowers are propelling the boat from one scenario to the next, the change in velocity divided by the initial velocity can be related to the change in wetted surface area divided by the initial wetted surface area. The same relation holds for a change in the coefficient of friction.

$$\frac{v_f}{v_0} = \sqrt[3]{\frac{S_0}{S_f}} \tag{19}$$

$$\frac{v_f}{v_0} = \sqrt[3]{\frac{C_0}{C_f}} \tag{20}$$

An increase in either the coefficient of friction or the wetted surface will lead to a decrease in shell velocity. Since the only external force acting on the shell is due to the frictional resistance between the shell and the water, equations 19 and 20 should be fairly accurate estimations of the effects of wetted surface area and coefficient of friction on shell speed.

The next source to consider is the effect of static weight. Static weight includes any mass that does not move with respect to the shell during the stroke cycle. For boat manufacturers, this refers to the total shell weight including riggers, foot stretchers, speakers, and wiring components. Static weight also includes the weight of the coxswain which usually has a minimum weight specific to the league in which the crew is competing.

Changing static weight, or deadweight, affects the shell speed directly by changing the equation of motion, and indirectly by changing the wetted surface area of the shell. The first step in determining the relationship between weight and velocity is to determine the relationship between weight and wetted surface area.

By assuming the shell has vertical sides, the height, dh, that the boat will submerge for a change in weight, dW, can be related to the length of the shell, the width of the shell, and the density of the water.

$$dh = \frac{dW}{\rho w L} \tag{21}$$

The change in wetted surface area, dS, can then be related to dh.

$$dS = 2L(dh) \tag{22}$$

Combining equations 21 and 22 gives the relationship between dW and dS which can then be used in equation 19 to determine the relationship between dW and dv.

$$\frac{S_f}{S_0} = \sqrt[3]{\left(\frac{W_f}{W_0}\right)} \tag{23}$$

$$\frac{v_f}{v_0} = \sqrt[9]{\left(\frac{W_0}{W_f}\right)} \tag{24}$$

Dynamic weight will have the same effect on increased wetted surface area as static weight, but will have a different effect on the acceleration during the drive and the deceleration during the recovery. An increase in dynamic weight will increase the accelerations and decelerations caused by the rowers change in momentum on the slide. On the other hand, dynamic weight will reduce the deceleration caused by the drag force on the shell in the same manner that static weight does. Because of these two changes in acceleration and deceleration, dynamic weight should have the same, or possibly a slightly smaller effect on shell speed as static weight.

The final sources of inefficiency are directly related to the rowers and their technique. The first source to consider is stroke length which is determined by the catch and release angles. Many coaches intentionally rig their shells so that each rower will have the same finish angle regardless of height and length of the rower. For this reason, only changes in catch angle are considered in determining the effects of stroke length on shell speed.

There are several reasons why some oarsmen have longer or shorter catches than others. The main reason is that the rower is simply much taller or shorter, with the other reasons being directly related to technique. It is a common belief in rowing that shell speed is determined by length, power, and stroke rating, but the exact relationship between stroke length and speed has not been enumerated.

A longer stroke allows a rower to do more work on the shell per stroke. Work is equal to the force multiplied by the displacement and power is work divided by time. In the case of a longer stroke, rowers will apply more power per stroke and therefore deliver more energy to the system. The work done by the blade during the drive is equal to the force on the blade integrated over the path of the blade through the stroke.

$$W_{blade} = \int_{catch}^{release} F L_o \, d\phi \tag{25}$$

The outboard length, $L_o$, is the radius of the arc that the blade travels through the drive and multiplying $L_o$ by the total angle of the drive will result in the distance traveled by the blade through the drive relative to the shell. Integrating equation 27 expresses the work done by the blade during the drive in terms of total drive angle.

$$W_{blade} = F_{ave} L_o (\phi_{release} - \phi_{catch}) \tag{26}$$

Since the catch angle is a negative value, a greater catch angle will result in a longer arc length and thus transfer more energy to the system. Here, the total swept angle of the stroke is what matters even though the finish angle is held constant. Holding stroke rating constant, the cycle time remains the same and the power ratio is then equal to the work ratio.

$$\frac{W_f}{W_0} = \frac{\phi_f}{\phi_0} \tag{27}$$

$$\frac{P_f}{P_0} = \frac{\phi_f}{\phi_0} \tag{28}$$

The equation refers to the change in total angle of the drive even though only the catch angle is being changed. From equation 18, we know that power is equal to the coefficient of friction multiplied by the cube of velocity. Substituting that relation into equation 28 gives the relationship between stroke length and velocity.

$$\frac{v_f}{v_0} = \sqrt[3]{\frac{\phi_f}{\phi_0}} \qquad (29)$$

This formula predicts that a stroke which is eight times as long will result in a shell speed that is twice the initial speed. This prediction should be fairly accurate even though the average force during the drive and the drive time are assumed to remain constant.

The next factor believed to have a significant influence on shell speed is stroke rating. The stroke rating is the number of stroke cycles completed in one minute and a typical race pace is around 36 strokes per minute. As the stroke rating increases, the drive time decreases, but more significantly, the recovery time decreases. The work per stroke does not increase significantly as the stroke rating increases, but the power per stroke does since the cycle time decreases. By assuming constant work per stroke, the power delivered at various stroke ratings can be calculated by combining the basic power formula with the formula to determine cycle time from stroke rating.

$$P_s = \frac{W}{t_{cycle}} \qquad (30)$$

$$t_{cycle} = \frac{60}{SR} \qquad (31)$$

$$\frac{P_f}{P_0} = \frac{SR_f}{SR_0} \qquad (32)$$

Similar to stroke length, stroke rating has a linear effect on power per stroke which can then be used in equation 18 to determine the relationship between stroke rating and shell speed.

$$\frac{v_f}{v_0} = \sqrt[3]{\frac{SR_f}{SR_0}} \qquad (33)$$

The final source of inefficiency considered in this study is the velocity profile of the recovery. Most coaches teach rowers to move with a constant speed on the recovery in an effort to reduce the amount of energy dissipated by the rower on the slide. Some coaches teach a slight pause at the release known as a gather, and other coaches teach rowers to get their hands and bodies out of bow as quickly as possible. Each of these three scenarios are modeled in the simulation in order to determine which case results in the faster shell speed, and whether or not one method is favored over another at various stroke ratings. Since there is no method to compare the different recoveries directly, the models of each were purely run through the simulation and no prediction was made. The velocity profiles of each scenario along with the position of the rower's center of mass are shown below.

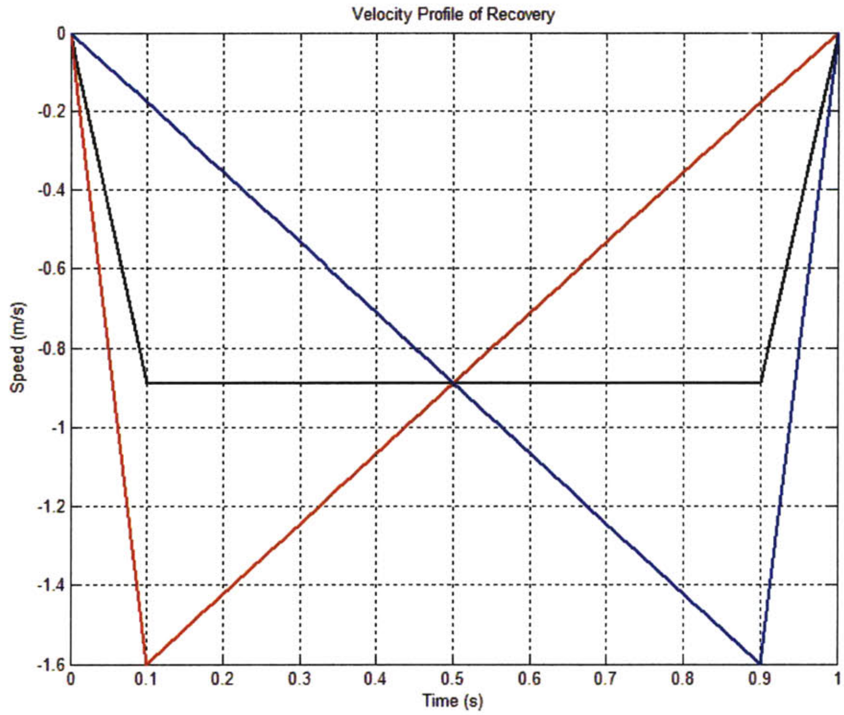


Figure 4: Velocity of Rower Mass during Recovery

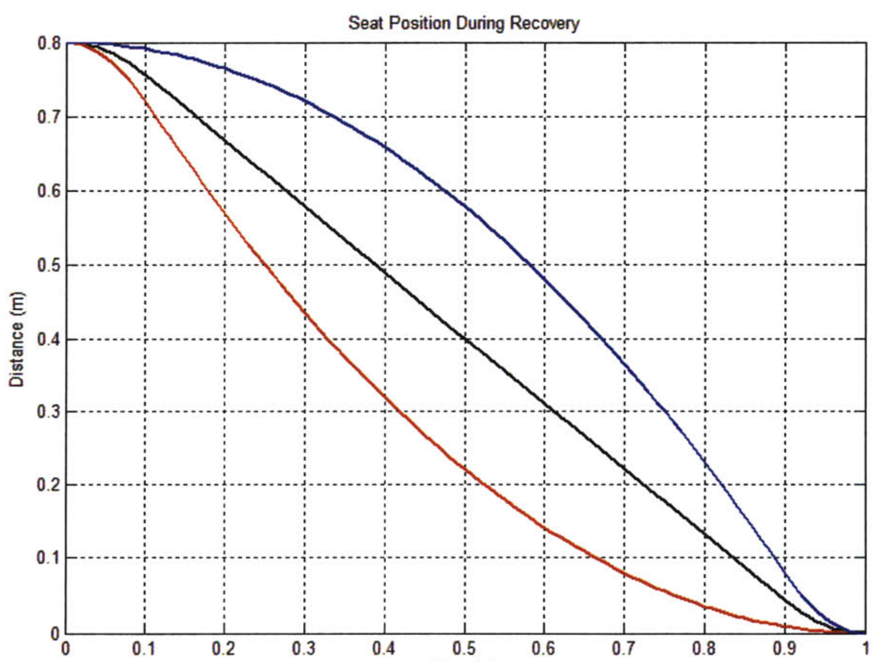


Figure 5: Rower Position during Recovery

Although the predictions and the model use similar equations to determine shell velocity, the predictions are based primarily on the relationship given by equation 18. This equation shows that the power is proportional to the cube of the shell velocity. The model only uses this relation to govern the interaction between the shell and the water. The rest of the model includes the complexities of the rowing cycle that are responsible for the accelerations and decelerations of the shell throughout the cycle. These complexities are excluded in the predictions which are based on a shell that travels at a constant velocity. The purpose of the first order predictions is to give a quick way of determining the effects of altering various parameters on the shell speed. The Simulink model is used purely to verify that these first order predictions are accurate even though they assume that the shell travels at a constant velocity.

## RESULTS

Stroke rating, drive length, wetted surface area, and coefficient of friction are predicted to have the greatest effects on shell speed. Static weight is expected to have a significantly smaller effect on shell speed with a slightly greater effect on speed than dynamic weight. The last source of inefficiency analyzed in this study was the velocity profile during the recovery which is predicted to have little or no effect on shell speed.

The first step to running the simulation was establishing a baseline for the testing. The initial parameters for the model are listed below:

$$S_0 = 12.0m^2$$

$$C_0 = 1.0\frac{Ns^2}{m^2}$$

$$W_{static} = 150.0kg$$

$$W_{dynamic} = 750.0kg$$

$$W_0 = 900.0kg$$

$$\phi_0 = 1.68rad$$

$$SR_0 = 30spm$$

The results of each test were plotted against the predicted model. Some tests such as wetted surface area, stroke length, static weight, and dynamic weight were performed at various stroke ratings to determine whether or not the prediction was accurate independent of stroke rating. The final plot is of the normalized results of the simulation in an effort to show the relative effects of each on shell speed.

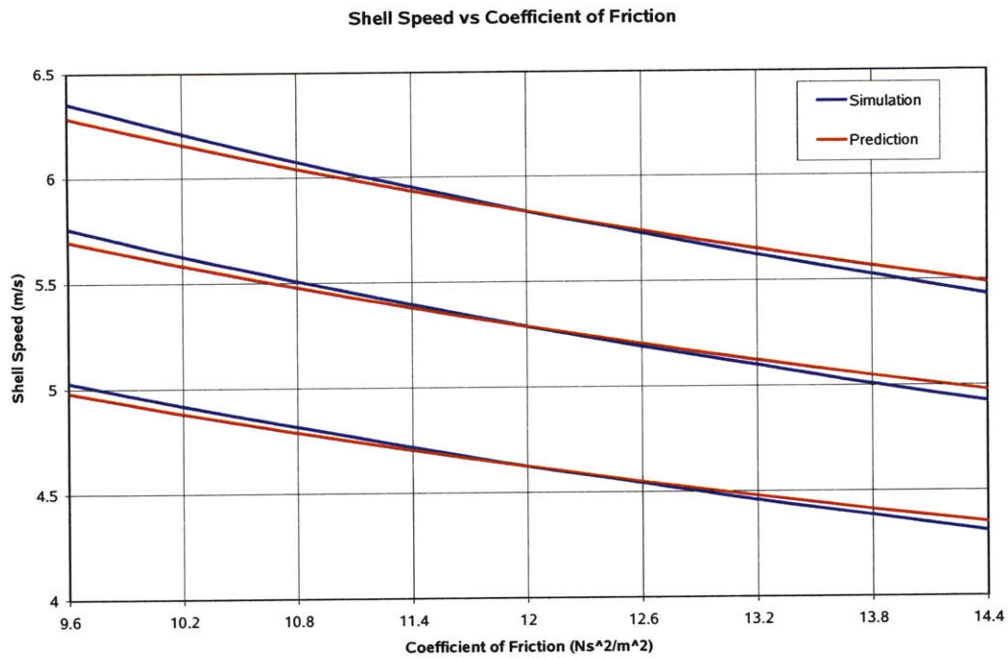


Figure 6: Simulation and prediction of shell speed versus the coefficient of friction

The total coefficient of friction is equal to the coefficient of friction due to surface roughness multiplied by the wetted surface area of the rowing shell. The simulation and prediction were repeated at stroke ratings of 20, 28, and 36 strokes per minute. The greater shell speeds correspond to higher stroke ratings. The effect of total coefficient of friction on shell speed is consistent regardless of stroke rating. The slope of the prediction is smaller than the simulation indicating that the prediction is a slight underestimation of the effect of coefficient of friction on shell speed.

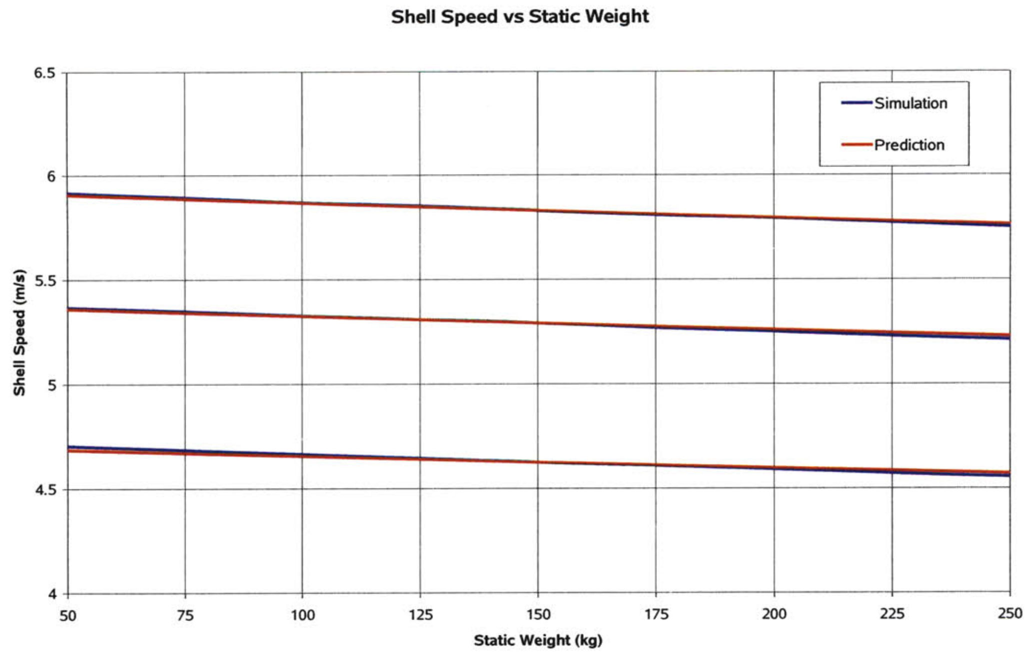


Figure 7: Simulation and prediction of shell speed versus static weight

Again, the simulation and prediction were performed at stroke ratings of 20, 28, and 36 strokes per minute with the greater shell speeds corresponding to higher stroke ratings. The figure again shows that the effect of weight on shell speed is consistent at various stroke rates. Here the prediction is again a slight underestimation of the actual effect.

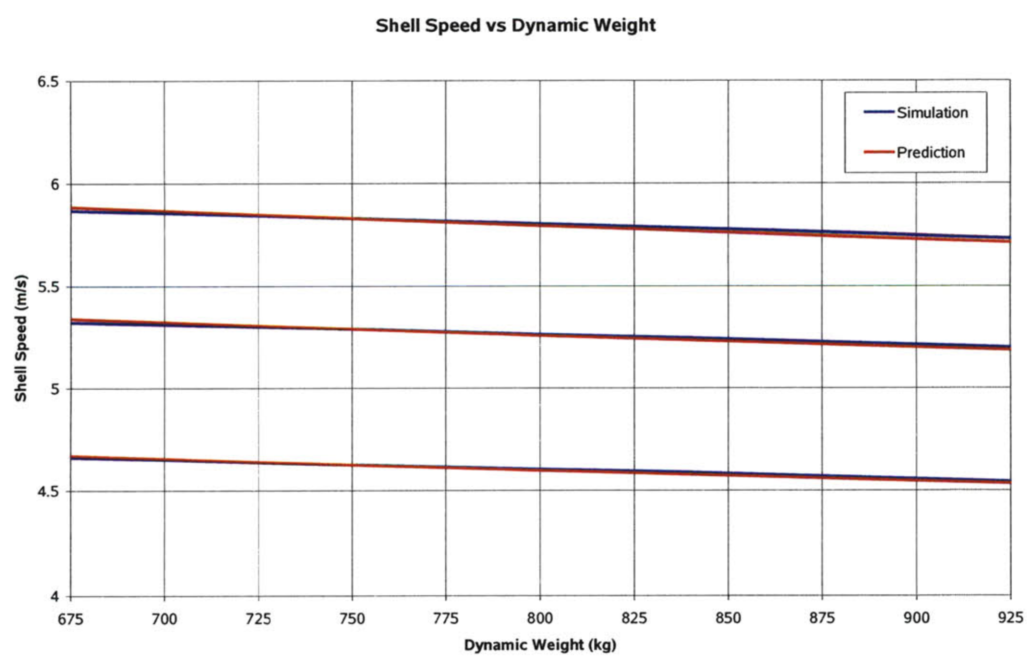


Figure 8: Simulation and prediction of shell speed versus dynamic weight

Similar to the first two tests, the simulation and prediction were performed at stroke ratings of 20, 28, and 36 strokes per minute. The figure shows that the effects of dynamic weight are very similar to those of static weight. It is cleat that dynamic weight has a significantly smaller effect on shell speed that coefficient of friction.

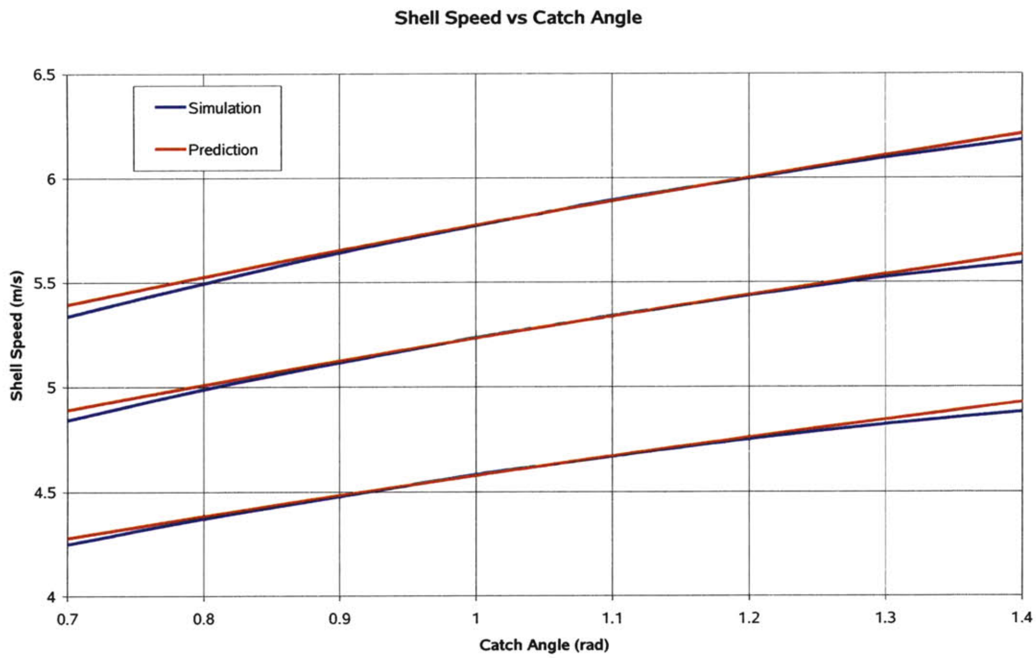


Figure 9: Simulation and prediction of shell speed versus catch angle

This test was also conducted at stroke ratings of 20, 28, and 36 strokes per minute. The relationship is roughly the same order of magnitude as that between coefficient of friction and shell speed. In this case, however, the prediction is a slight overestimation of the effect of drive length on shell speed. This means that the normalized plot should show coefficient of friction having a slightly greater effect on shell speed than drive length.


Figure 10: Simulation and prediction of shell speed versus stroke rating

The prediction for the effect of stroke rating on shell speed is clearly an underestimation which means that stroke rating will most likely have the greatest effect on shell speed of all factors tested in this study.

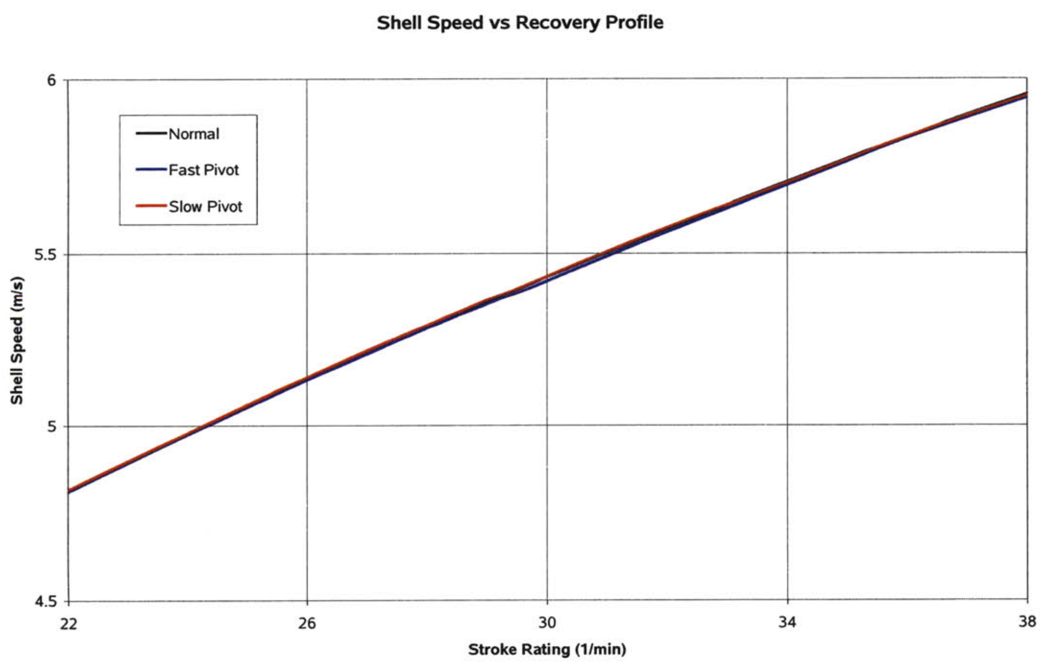


Figure 11: Simulation of shell speed versus velocity profile of recovery

As predicted, the velocity profile of the recovery has little to no effect on shell speed. The simulation shows that the relationship between acceleration of the slide on the recovery and shell speed is constant regardless of stroke rating. If anything, it looks like getting the hands and body out of bow as fast as possible slows the shell a fraction of a percent in terms of shell speed.

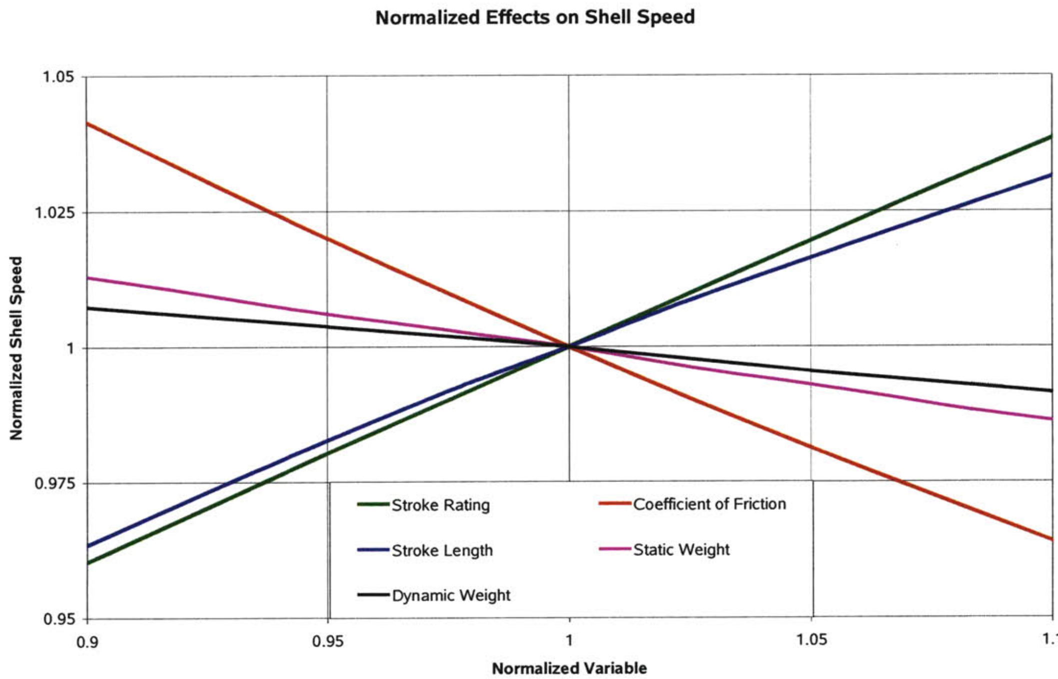


Figure 12: Normalized simulation results of various sources of inefficiency on shell speed

The curves with the greatest slopes have the most significant effect on shell velocity. From the plot it is clear that stroke rating has the greatest effect on shell speed, followed closely by wetted surface area and coefficient of friction. Just behind those is stroke length with static weight and dynamic having the smallest effects on shell speed. As predicted, dynamic weight has a smaller effect on shell speed than static weight.

## CONCLUSION

Using first order predictions and a MATLAB model of the rowing cycle, the extent to which a source of inefficiency in rowing affects shell speed was determined. With respect to the manufacturer, the greatest inefficiencies are due to the wetted surface area and the coefficient of friction. Some companies have made various attempts to reduce both the coefficient of friction and the wetted surface area by wet-sanding the shells after they are painted, and reducing the overall length of the shell by several feet. In actuality, manufacturers can only make efficiency gains of about five percent which correspond to speed increases of around 1.5 percent. For heavyweight men, this translates to roughly five seconds over a 2000 meter race.

The results of the simulation and predictions show that there are clearly more gains to be made by teaching rowers to maximize their stroke length and teaching them to row at higher stroke ratings. A five degree increase in stroke length will result in the same effect on shell speed as decreasing the wetted surface area by five percent. This is much easier to accomplish than redesigning a new shell with less wetted surface area. Even more drastically, racing at 36 strokes per minute as opposed to 34 strokes per minute will result in a two percent increase in shell speed. This corresponds to roughly seven seconds over 2000 meters.

The static weight and dynamic weight of the system have much less significant effects on shell speed than any of the other parameters tested. As opposed to gains of five or more seconds over 2000 meters, a five percent decrease in static or dynamic weight will only lead to a gain of one or two seconds over the same distance. The results of the simulation confirm the belief that shell speed is most directly related to length, power, and stroke rating. Manufacturers have little room to improve on the shells that already exist, and it is up to the coaches to teach their rowers to be as efficient as possible in order to make it down the course in the least amount of time.

# APPENDIX
## Matlab files used in rowing simulation

```
% angvel.m
% Stephen Young
% Effects of Various Inefficiencies in Rowing on Shell Speed
% Adapted from Marinus van Holst's Simulation of Rowing

% Determines angular velocity of oar throughout the drive

function yphi_dot = angvel(vfi)
global L_o FB_max % variables assigned in shell.m used in angvel.m
v_shell = vfi(1); % determine values of v_shell and phi
phi = vfi(2);

phi_dot = v_shell*cos(phi)/(L_o); % determines current angular velocity
dphi_dot = 0.1;                    % angular acceleration of oar
F_bladeR = forcerf(phi)*FB_max;    % determines blade force for a given
angle
if F_bladeR < eps
    F_bladeR = 0.1;
end;
F_blade = 0; % initial value for blade force
count = 0;
while (F_blade/F_bladeR <1) && (count < 100)
   count = count + 1;
   foud = F_blade;
   phi_dot = phi_dot+dphi_dot;
   vec = vblade(v_shell, phi, phi_dot); % determines u and angle of
   attack from vblade.m
   F_blade = fblade(vec(2), vec(1));     % determines F_blade from
   fblade.m
if F_blade/F_bladeR > 1.001   % determines blade force after FB_max is
   reached
     F_blade = foud;
     phi_dot = phi_dot-dphi_dot;
     dphi_dot = dphi_dot/2;
   end
end;
yphi_dot = [phi_dot F_bladeR];
```

```
% cblade.m
% Stephen Young
% Effects of Various Inefficiencies in Rowing on Shell Speed
% Adapted from Marinus van Holst's Simulation of Rowing

% Determines the lift and drag coefficients on the blade for all angles
of attack

function yc = cblade(alpha) % alpha is angle of attack of blade
global C_max
if abs(alpha) <= eps % eps = very small value slightly greater than 0
  Cd = 0;
  Cl = 0;

  % The following relations are from research done by
  % Nicholas Caplan & Trevor N. Gardner

else
  Cd = 2 * C_max * sin(alpha).*sin(alpha);
  Cl = C_max * sin(2*alpha);
end
yc = [Cd Cl];    % stores the lift and drag coefficients to be used in
                 other files
```

```
% fblade.m
% Stephen Young
% Effects of Various Inefficiencies in Rowing on Shell Speed
% Adapted from Marinus van Holst's Simulation of Rowing

% Determines force on blade surface during the drive

function F_blade = fblade(alpha, u)
global rho A_blade
vec = cblade(alpha); % att is the angle of attack of the blade
Cd = vec(1); % receives drag coefficient from cblade.m
Cl = vec(2); % recieves lift coefficient from cblade.m
xx = 0.5*rho*A_blade*u^2;  % xx is placeholder for denominator of force
                             equation
Fdrag = Cd*xx;
Flift = Cl*xx;
F_blade = sqrt(Fdrag^2 + Flift^2);
```

```
% forcerf.m
% Stephen Young
% Effects of Various Inefficiencies in Rowing on Shell Speed
% Adapted from Marinus van Holst's Simulation of Rowing

% Determines current blade force divided by max blade force

function yfor = forcerf(phi)
global phi_vsp yphi_vsp
if(phi<phi_vsp(1)) || (phi>phi_vsp(length(phi_vsp)))
    yfor=0; % sets F_blade to 0 at catch and release
else
yfor = interp1(phi_vsp, yphi_vsp, phi); % interpolates spline to
                                          determine F_blade
end
```

```
% main.m
% Stephen Young
% Effects of Various Inefficiencies in Rowing on Shell Speed
% Adapted from Marinus van Holst's Simulation of Rowing

% Determines phase of stroke (drive or recovery)
% Determines ydot, phi_dot, and F_blade for drive and recovery

function com = main(vec)

global phi_c phi_r phi_tot L_slide step tREC drive

phi = vec(1);
v_shell = vec(2);
y = vec(3);


if drive == true && phi>(phi_r-0.002)  % transition from drive to
                                       recovery
    drive = false;       % ends drive and starts recovery
    phi = phi_r;         % phi = release angle
    y = L_slide;         % position of rower is at max slide length
    tREC = -step;
end
if drive == false && phi<(phi_c+0.002) % transition from recovery to
                                       drive
    drive = true; % ends recovery and starts drive
    phi = phi_c;  % phi = catch angle
    y = 0;        % position of rower is at minimum slide length
end
if drive == true % drive phase of stroke cycle
    vec2 = angvel([v_shell phi]);
    phi_dot = vec2(1);  % phi_dot determined in angvel.m
    F_blade = vec2(2);  % F_blade determined in angvel.m
    ydot = stroke([phi_dot phi]);
else                     % recovery phase of stroke cycle
    F_blade = 0.0;       % F_blade = 0 throughout recovery
    ydot = recovery(y);
    phi_dot = ydot*phi_tot/L_slide; % determines phi_dot of recovery
 end;
 com = [phi_dot F_blade ydot];
```

```
% powbl.m
% Stephen Young
% Effects of Various Inefficiencies in Rowing on Shell Speed
% Adapted from Marinus van Holst's Simulation of Rowing

% Determines v_shell, Fblade, phi_dot, and phi from rowsim.mdl

function yPbl = powbl(vec)
global L_o
v_shell = vec(1);
F_blade = vec(2);
phi_dot = vec(3);
phi = vec(4);

yy = (phi_dot*L_o-v_shell*cos(phi))*F_blade; % yy = power generated by
blade
if yy<0
    yy=0;
end
yPbl=yy;
```

```
% powdrag.m
% Stephen Young
% Effects of Various Inefficiencies in Rowing on Shell Speed
% Adapted from Marinus van Holst's Simulation of Rowing

% Determines power dissipated by frictional drag on shell

function yPx = powdrag(vec)
global C_tot
v_shell = vec(1); % v_shell determined from rowsim.mdl
yPx = v_shell^3*C_tot;
```

```
% powoar.m
% Stephen Young
% Effects of Various Inefficiencies in Rowing on Shell Speed
% Adapted from Marinus van Holst's Simulation of Rowing

% Determines power delivered to oar by rower

function yPoar = powoar(vec)
global L_o
F_blade = vec(2);
phi_dot = vec(3);
yy = F_blade*phi_dot*L_o; % yy = oar power
if yy<0
    yy=0;
end
yPoar=yy;
```

```
% recovery.m
% Stephen Young
% Effects of Various Inefficiencies in Rowing on Shell Speed
% Adapted from Marinus van Holst's Simulation of Rowing

% Determines recovery speed and position for different recovery profiles

function ydotR = recovery(y)
global L_slide A1 A2 A3 A4 tREC step p_ave VR_ave VR_max T_rec T_ave
T_max
tREC = tREC + step;
 if tREC <= T_ave % used for first 3 recovery profiles
 % if tREC <= T_rec-T_ave % used for 4th recovery profile
      ydot = A1*tREC; % used for all recovery profiles
      y = L_slide+0.5*A1*tREC^2; % used for all recovery profiles
  else if tREC <= T_max % used for 1st recovery profile
      ydot = VR_ave+A2*(tREC-T_ave);
      y = L_slide+0.5*A1*T_ave^2+VR_ave*(tREC-T_ave)+0.5*A2*(tREC-
      T_ave)^2;
  else if tREC <= (1-p_ave)*T_rec % used for first 2 recovery profiles
      ydot = VR_max+A3*(tREC-T_max); % used for 1st recovery profile
      y = L_slide+0.5*A1*T_ave^2+VR_ave*(T_max-T_ave)+0.5*A2*(T_max-
      T_ave)^2+VR_max*(tREC-T_max)+0.5*A3*(tREC-T_max)^2; % used for
      1st recovery profile
      % ydot = VR_max; % used for 2nd recovery profile
      % y = L_slide+0.5*A1*T_ave^2+VR_max*(tREC-T_ave); % used for 2nd
      recovery profile
 else
      ydot = VR_ave + A4*(tREC-T_rec+T_ave); % used for 1st recovery
                                              profile
      y = L_slide+0.5*A1*T_ave^2+VR_ave*(T_max-T_ave)+0.5*A2*(T_max-
      T_ave)^2+VR_max*(T_rec-T_ave-T_max)+0.5*A3*(T_rec-T_ave-
      T_max)^2+VR_ave*(tREC-T_rec+T_ave)+0.5*A4*(tREC-T_rec+T_ave)^2; %
      used for 1st recovery profile
      % ydot = VR_max + A2*(tREC-T_rec+T_ave);  % used for 2nd recovery
                                                  profile
      % y = L_slide+0.5*A1*T_ave^2+VR_max*(tREC-T_ave)+0.5*A2*(tREC-
      T_rec+T_ave)^2; % used for 2nd recovery profile
      % ydot = VR_max + A2*(tREC-T_ave);  % used for 3rd recovery
                                            profile
      % y = L_slide+0.5*A1*T_ave^2+VR_max*(tREC-T_ave)+0.5*A2*(tREC-
      T_ave)^2; % used for 3rd recovery profile
      % ydot = VR_max + A2*(tREC-T_rec+T_ave);  % used for 4th recovery
                                                  profile
      % y = L_slide+0.5*A1*(T_rec-T_ave)^2+VR_max*(tREC-T_rec+T_ave)
      +0.5*A2*(tREC-T_rec+T_ave)^2; % used for 4th recovery     profile
      end
      end
 end
  ydotR = ydot;
```

```
% results.m
% Stephen Young
% Effects of Various Inefficiencies in Rowing on Shell Speed
% Adapted from Marinus van Holst's Simulation of Rowing

% Determines outputs of rowsim.mdl

global T_rec L_o
n = length(phi_dot);
i = n;
if (phi_dot(n)<0) % simulation ended in recovery phase
   while (phi_dot(i)<0)
     i=i-1;
   end
   while (phi_dot(i)>=0)
     i=i-1;
   end
   n2=i;
else % simulation ended in drive phase
   while (phi_dot(i)>0)
     i=i-1;
   end
   n2=i;
end
while (phi_dot(i)<0) % runs through recovery phase
  i=i-1;
  end
while (phi_dot(i)>=0) % runs through drive phase
  i=i-1;
  end
n1 = i+1; % n1 = start of drive
i = n1;
while phi_dot(i)>0 i=i+1; end
n3 = i-1; % n3 = transition from drive to recovery
tn3 = time(n3)-time(n1);

% Final Calculations

W_blade = Ebl(n2)-Ebl(n1); % work done by blade
W_drag = Edrag(n2)-Edrag(n1); % work of friction on boat
W_oar = Eoar(n2)-Eoar(n1); % work transferred to oar
W_tot = W_blade+W_drag+W_rec; % total work in one stroke
T = time(n2)-time(n1); % time to complete one stroke cycle
SR = 60/T; % stroke rating (1/min)
P_row = E_tot/T; % power delivered by rower (W)
P_oar = E_oar/T; % power transferred to oar in one stroke (W)
v_ave = (xout(n2)-xout(n1))/T; % average shell speed (m/s)
T2k = 2000/v_ave; % time to complete 2000 m (s)
t_cycle = time(n1:n2)-time(n1); % time to complete a cycle starting at
t = 0
figure(1); % plot shell speed during one stroke cycle
plot(t_cycle, vel(n1:n2), 'r', 'LineWidth', 2);
hold on
plot([tn3 tn3], [0 7],'c', 'LineWidth', 1.5);
axis([0 max(t_cycle) 0 7]);
grid;
xlabel('Time (s)');
```

```
ylabel('Shell Speed (m/s)');
title('Shell Speed during One Cycle');

% Display Results
fprintf(1,'------- initial data -------\n')
s1='  m_s     m_r     FB_max    L_o     phi_c    phi_r     L_slide     T_rec';
s2='  kg      kg        N        m        rad      rad         m           s  ';
fprintf(1, '%s\n',s1)
fprintf(1, '%s\n',s2)
fprintf(1,...
'%5.1f %5.1f %5.0f %4.2f %5.2f   %4.2f %5.2f %5.2f %6.2f\n',...
m_s,m_r,FB_max,L_o,phi_c,phi_r,L_slide,T_rec)
fprintf(1,'\n')
s10='  A_blade       C_tot         C_max         spr';
s11='     m2         N.s2/m2          -          m/s';
fprintf(1, '%s\n',s10)
fprintf(1, '%s\n', s11)
fprintf(1,...
' %6.3f    %6.2f     %5.2f    %6.2f\n', A_blade, C_tot, C_max, VR_max)
fprintf(1,'\n')
fprintf(1,'------- results -------\n')
s3=' W_blade       W_drag        W_rec        W_tot        T';
s4='    J              J            J            J          s';
fprintf(1, '%s\n', s3)
fprintf(1, '%s\n', s4)
fprintf(1,...
'%7.2f   %7.2f   %7.2f   %7.2f   %4.3f    %5.2f\n', W_blade, W_drag,
W_rec, W_tot, T)
fprintf(1,'\n')
s5=' SR     T2000      Prow         Poar          vel';
s6=' m-1     sec         W            W           m/s';
fprintf(1, '%s\n',s5)
fprintf(1, '%s\n', s6)
fprintf(1,...
'%6.2f  %6.1f   %6.2f   %6.2f  %6.3f\n', SR, T2k, P_row, P_oar, v_ave)
```

```
% shell.m
% Stephen Young
% Effects of Various Inefficiencies in Rowing on Shell Speed
% Adapted from Marinus van Holst's Simulation of Rowing

clc; clear all;

global C_max phi_c phi_r phi_tot rho A_blade L_o FB_max...
       VR_max L_slide T_rec T_max C_tot m_tot m_rat m_inv drive step...
       phi_v yphi_v phi_vsp yphi_vsp A1 A2 A3 A4 tREC

% determine force on surface of blade through drive
C_max = 1.2; % maximum lift and drag coefficient
phi_c = -1.05; % catch angle
phi_r = 0.63; % release angle
phi_tot = phi_r-phi_c;
phi_v  = [phi_c  phi_c+0.2  phi_c+0.4  phi_r-0.6  phi_r];
yphi_v = [0        0.6         1.0         1.0        0];
phi_vsp = phi_v(1):0.01:phi_v(5); % plots values used for force curve
yphi_vsp = spline(phi_v, yphi_v, phi_vsp); % smooths blade force curve
yphi_vsp = yphi_vsp/max(yphi_vsp);
figure(1); % plot blade force curve
plot(phi_v, yphi_v, 'k', 'LineWidth', 2);
grid;
title('Blade Force versus Oar Angle');
xlabel('Oar Angle (rad)');
ylabel('Normalized Blade Force');
axis([phi_c-0.1 phi_r+0.1 0 1.1]);
hold on;
plot(phi_vsp, yphi_vsp, 'r', 'LineWidth', 2);
hold on;

%set constants and variables
drive = true; % simulation starts in drive phase
tREC = 0;
step = 0.001; % step size
rho = 1000; % density of water (kg/m^3)
A_blade = 0.12; % surface area of blade (m^2)
L_o = 2.5; % outboard length of oar (m)
L_slide = 0.8; % slide length (m)
FB_max = 8*250; % max force on blade multiplied by 8 rowers (N)
m_s = 150; % weight of shell + coxswain (kg)
m_r = 750; % weight of 8 rowers
m_tot = m_s+m_r; % total weight of system
m_rat = m_r/m_tot; % ratio of dynamic weight to total weight
m_inv = 1/m_rat; % inverse mass ratio
A_wetted = 12.0; % wetted surface area of shell (m^2)
C_fric = 1.0; % coefficient of friction (N*s^2/m^4)
C_tot = C_fric*A_wetted; % total coefficient of friction (N*s^2/m^2)

% ------------- recovery ----------------

T_rec = 1.5; % total recovery time
p_ave = 0.1; % fraction of recovery time to get to average velocity
p_max = 0.4; % fraction of recovery time to get to max velocity
T_ave = p_ave*T_rec; % time to get to average velocity
T_max = p_max*T_rec; % time to get to max velocity
```

```
VR_ave = -L_slide/T_rec; % average slide speed
VR_max = 1.25*VR_ave; % max slide speed
% VR_max = -1.1111*VR_ave; % used for 2nd recovery profile
% VR_max = -2*VR_ave; % used for 3rd and 4th recovery profiles
A1 = VR_ave/T_ave; % slide acceleration to VR_ave
A2 = (VR_max-VR_ave)/(T_max-T_ave); % slide acceleration to VR_max
A3 = (VR_ave-VR_max)/(T_rec-T_ave-T_max); % slide deceleration to VR_ave
A4 = -A1; % slide deceleration to 0
% A1 = VR_max/T_ave; % used for 3rd recovery profile
% A2 = -VR_max/(T_rec-T_ave); % used for 3rd recovery profile
% A1 = VR_max/(T_rec-T_ave); % used for 4th recovery profile
% A2 = -VR_max/T_ave; % used for 4th recovery profile

% for loop to run through recovery
t = 0:0.01:T_rec;
n = length(t);

% used to plot different recovery profiles; same as recovery.m
for i = 1:n
  if t(i) <= T_ave
  % if t(i) <= T_rec-T_ave
        ydot(i) = A1*t(i);
        y(i) = L_slide+0.5*A1*t(i)^2;
    else if t(i)<= T_max
        ydot(i) = VR_ave+A2*(t(i)-T_ave);
        y(i) = L_slide+0.5*A1*T_ave^2+VR_ave*(t(i)-T_ave)+0.5*A2*(t(i)-
        T_ave)^2;
    else if t(i) <= T_rec-T_ave
        ydot(i) = VR_max+A3*(t(i)-T_max);
        y(i) = L_slide+0.5*A1*T_ave^2+VR_ave*(T_max-T_ave)
        +0.5*A2*(T_max-T_ave)^2+VR_max*(t(i)-T_max)+0.5*A3*(t(i)-
        T_max)^2;
        % ydot(i) = VR_max;
        % y(i) = L_slide+0.5*A1*T_ave^2+VR_max*(t(i)-T_ave);
    else
        ydot(i) = VR_ave + A4*(t(i)-T_rec+T_ave);
        y(i) = L_slide+0.5*A1*T_ave^2+VR_ave*(T_max-T_ave)
        +0.5*A2*(T_max-T_ave)^2+VR_max*(T_rec-T_ave-T_max)
        +0.5*A3*(T_rec-T_ave-T_max)^2+VR_ave*(t(i)-T_rec+T_ave)
        +0.5*A4*(t(i)-T_rec+T_ave)^2;
        % ydot(i) = VR_max + A2*(t(i)-T_rec+T_ave);
        % y(i) = L_slide+0.5*A1*T_ave^2+VR_max*(t(i)-T_ave)
        +0.5*A2*(t(i)-T_rec+T_ave)^2;
        % ydot(i) = VR_max + A2*(t(i)-T_ave);
        % y(i) = L_slide+0.5*A1*T_ave^2+VR_max*(t(i)-T_ave)
        +0.5*A2*(t(i)-T_ave)^2;
        % ydot(i) = VR_max + A2*(t(i)-T_rec+T_ave);
        % y(i) = L_slide+0.5*A1*(T_rec-T_ave)^2+VR_max*(t(i)-
        T_rec+T_ave)+0.5*A2*(t(i)-T_rec+T_ave)^2;
         end
         end
  end
end

figure(2); % plot velocity profile of recovery
plot(t, ydot, 'k', 'LineWidth', 2);
title('Velocity Profile of Recovery');
```

```
xlabel('Time (s)');
ylabel('Speed (m/s)');
grid;
% pause
figure(3); % plot seat position during recovery
plot(t, y, 'r', 'LineWidth', 2);
title('Seat Position During Recovery');
xlabel('Time (s)');
ylabel('Distance (m)');
grid;
```

```
% slide.m
% Stephen Young
% Effects of Various Inefficiencies in Rowing on Shell Speed
% Adapted from Marinus van Holst's Simulation of Rowing

% Constrains slide position to total length of slide
% yy is used as a placeholder for y while determining slide position

function yy = slide(y)
global L_slide
if y >L_slide
    yy = 0.99*L_slide;
else
    yy = y;
end
```

```
% stroke.m
% Stephen Young
% Effects of Various Inefficiencies in Rowing on Shell Speed
% Adapted from Marinus van Holst's Simulation of Rowing

% Determines instantaneous seat speed
% Determines phi_dot and phi from rowsim.mdl

function ydot = stroke(vec)
global phi_tot L_slide phi_c
phi_dot = vec(1);
phi = vec(2);
aux = pi/(phi_tot);
ydot = L_slide/2*aux*sin(aux*(phi-phi_c))*phi_dot;
```

```
% vblade.m
% Stephen Young
% Effects of Various Inefficiencies in Rowing on Shell Speed
% Adapted from Marinus van Holst's Simulation of Rowing

% Determines blade velocity with respect to water

function yblade = vblade(v_shell, phi, phi_dot)
global L_o
u_per = phi_dot*L_o-v_shell*cos(phi); % perpindicular blade velocity
u_lat = v_shell*sin(phi); % lateral blade velocity
u = sqrt(u_per^2 + u_lat^2); % combined blade velocity
if (abs(u_lat)<0.001)
   alpha = pi/2;
else
   alpha = abs(atan(u_per/u_lat)); % determines angle of attack of blade
end

if alpha > pi/2
  alpha = alpha-pi/2;
end
yblade = [u alpha];
```

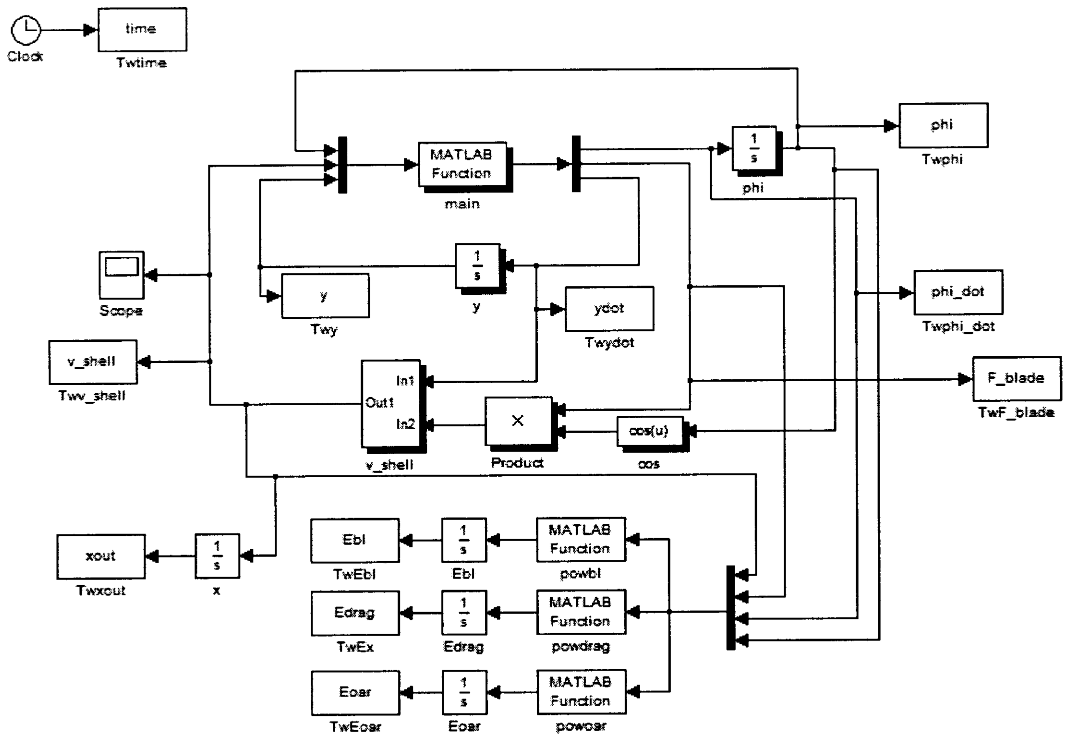


Figure 13: rowsim.mdl adapted from Marinus van Holst's Simulation of Rowing

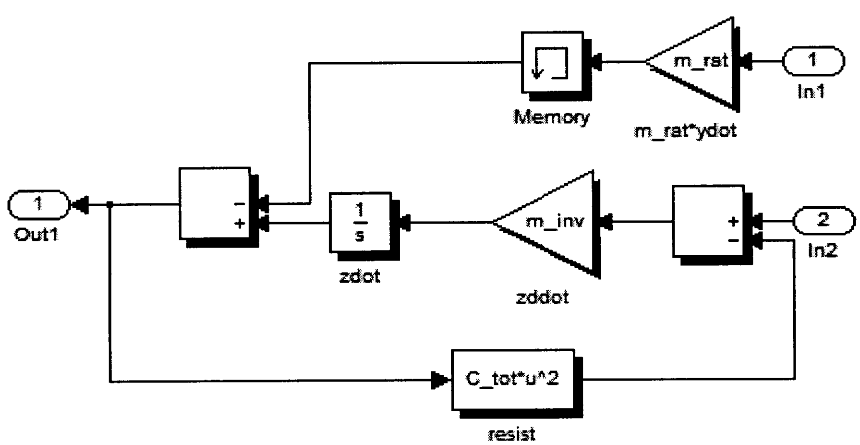


Figure 14: rowsim.mdl/v_shell adapted from Marinus van Holst's Simulation of Rowing

ACKNOWLEDGEMENT

I would like to thank Marinus van Holst for providing me with his MATLAB files that he wrote for his Simulation of Rowing website. The files allowed me to test my predictions about inefficiencies of rowing without the need of performing on the water testing. They also confirmed the theories I developed about the relations between various parameters in rowing and shell speed. Furthermore, they taught me a better understanding of the complex rowing cycle.

# BIOGRAPHY

Stephen F. Young, Jr is the varsity heavyweight men's coxswain at MIT. He has been coxing since his freshman year in high school and plans to compete in the 2009 Senior World Championships in Poznan, Poland. His ultimate goal is to race in the men's heavyweight eight at the London 2012 Olympics. He will be earning his bachelors degree in mechanical engineering from the Massachusetts Institute of Technology and will continue his studies to earn a masters degree in naval architecture. Stephen has aspirations of designing, building, and racing America's Cup yachts.

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