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# Dynamic modeling of ergometer and on-water rowing

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*Indoor rowing, which began as a means of keeping fit when conditions do not allow training on the water, has become a sport in its own right, and indoor rowers are found in gyms and fitness clubs worldwide and performed by many athletes for cross-training and conditioning. A mathematical model is presented and is used to analyze the dynamics of a rower in a single scull on the water and to compare these with the dynamics of the ergometer system. The results show that while the ergometer provides an acceptable simulation of the entire system dynamics, it cannot simulate the movement of the boat during the recovery, the sensitivity of the boat to movement of the body during the recovery when the blades are out of the water. The model shows that the hull speed of the boat, and hence the drag on the boat, is highest during the recovery, and hence underlines the importance of technique during the recovery to the overall speed of the boat on the water. It can be concluded that the ergometer is a useful training tool for rowers and other athletes, but it cannot improve poor technique or teach good technique.* 

**Keywords:**
- rowing
- ergometer
- sculling
- dynamics
- modeling
- drag

## 1. INTRODUCTION

Indoor rowing, which began as a training tool for competitive oarsmen and women at times when training on the water was not available—during Atlantic crossings and when the rivers were iced over—has become a sport in its own right, with its own national championships and world records. One of the most successful and widely-accepted indoor rowing machines is the concept 2 indoor rower, shown in Figure 1. The rower has a sliding seat and footplate, and rows by pulling on the handle attached to a chain. The chain drives a flywheel during the power stroke via a ratchet, and recoils under tension from a bungee cord during the recovery. The resistance and damping can be adjusted by changing the aperture area for flow entering the device, which functions as a rather inefficient centrifugal pump, and a performance monitor is provided to allow the rower to keep track of speed, distance traveled, power output, and time elapsed. Viscous drag due to the air being pumped through the flywheel enclosure provides a resistance, which can be taken to be proportional to the rotational speed of the fan.

In a single scull, the sculler sits on a sliding seat and is fixed to the boat by the shoes on the footrest. The oars (sculls) act as second class levers, with the pivot point at or near the junction between the shaft of the scull and the blade. The effort of the sculler is applied at the handle and transmitted through the oarlock (gate) to the rigger. This force serves to drive the boat during the power phase of the rowing stroke. Drag on the boat comes in the form of viscous or skin friction drag (proportional to the boat velocity), form drag due to the formation of a wake (dependent on hull form and proportional to boat velocity), and wave drag (proportional to boat length and the square root of the velocity) due to the formation of a bow and stern wave.

## 2. METHODS

### 2.1 Biomechanics

#### 2.1.1 Ergometer

For the rowing machine, the force is always tangential to the flywheel, hence it can be assumed that 100% of the effort of

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Figure 1. Concept 2 model C indoor rower [1]. © 2008 Taylor and Francis. Reproduced by kind permission.

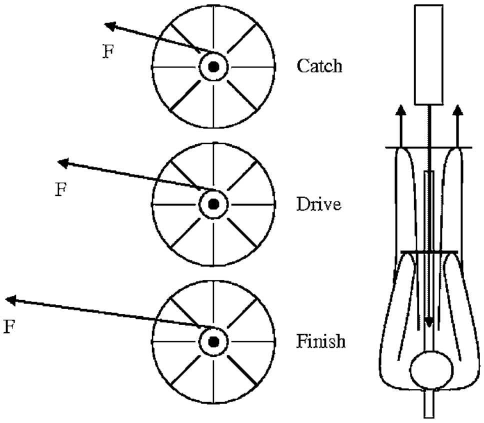


Figure 2. Schematic showing system of force transmission from rower to ergometer flywheel.

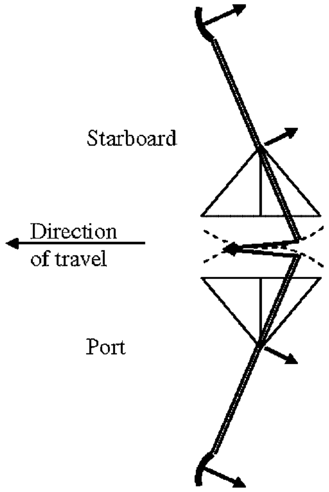


Figure 3. Transmission of force from rower to water through the sculls. Dashed lines indicate the movement of the sculls during the stroke.


Figure 4. Phases of the rowing stroke in a single scull [1]. © 2008 Taylor and Francis. Reproduced by kind permission.

the rower is transmitted to it, as shown in Figure 2. The tension in the chain acting on the flywheel, is equal to the effort exerted by the rower. In addition, the force application is a direct pull in the line of the body as shown. It has been noted that loading on the footplate of a concept 2 ergometer is higher than it would be in a boat, partly due to the lack of a reaction force applied at the rigger (see Figure 3) and partly due to the design of the machine [2–4]. A competing design, the Row-Perfect ergometer (RowPerfect, Sydney, NSW, Australia) addresses this by allowing the flywheel to move relative to the rower, and setting the weight of the flywheel assembly to be similar to that of the boat, following on-water dynamics of the sculler and the boat more closely; however, the system resistance is still based on a spinning flywheel and damper, and hence this relative motion serves principally to mitigate loading on the legs and feet at the catch, giving a more 'boat-like' feel [4].

### 2.1.2 Sculling boat

On the water, the sculler is pulling on the handles of the oars, which in turn exert force on the boat and the water. Since the force from the sculler's arm is not always perpendicular to the oar shaft and the force exerted on the water is not always in the direction of travel (Figure 3), there will be losses in the system and a variation in the efficiency of the exertion of force. Most non-novice scullers will push outwards slightly on the handle of the scull to hold the scull against the gate, allowing greater control of the sculls.

The various phases of the sculling stroke on the water are shown in Figure 4. As can be seen, the sculler is at full

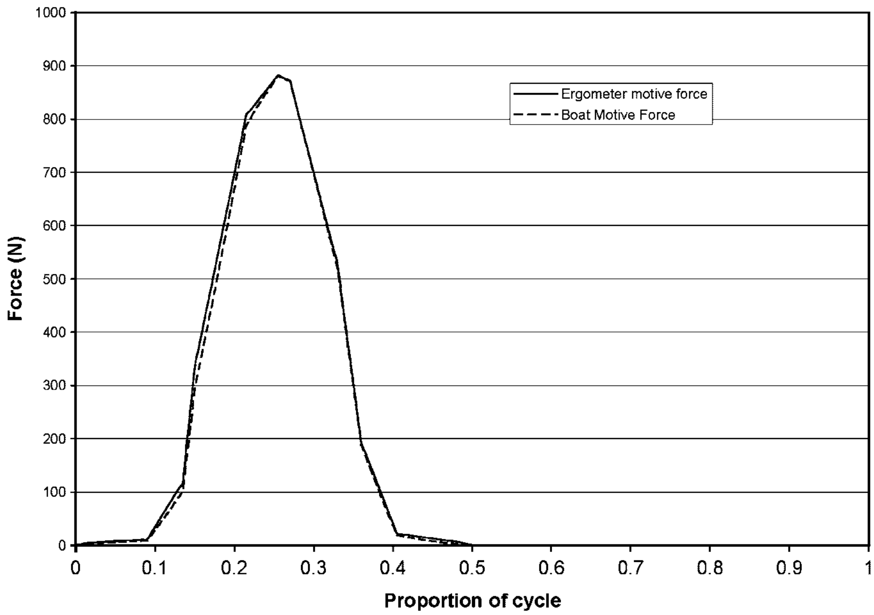


**Figure 5.** Force input throughout the cycle. Rating is taken as 30 strokes/min, hence one cycle corresponds to 2 s. Boat motive force is adjusted to compensate for the angle between the scull and the water.

compression at the catch, when the oars enter the water and the force is applied. At this point, the legs are biomechanically weakest as they are flexed, and the muscles used in the drive are close to their maximum length [5]. A similar situation occurs on the rowing machine, which can be taken to be the same for leg and torso movement. However, the movements of the arms on the rowing machine are markedly different, as there is no rotation necessary in the shoulders, and the handle follows a straight line, unlike the arc described by the handles of the sculls.

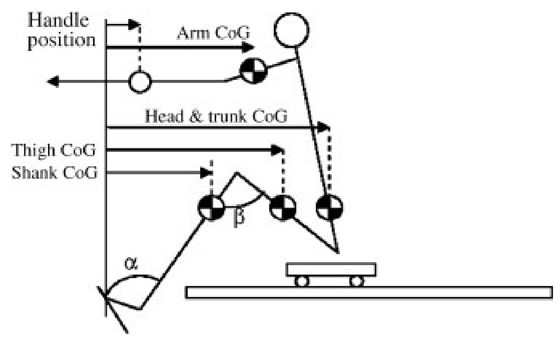


**Figure 6.** Joint angles used in the calculation of position of centers of mass (COG) relative to foot stretcher. Hip angles are estimated from the data of Upson [3]. Proportions for the body are taken from human anthropomorphic data [5].

### 2.2 Computational Modeling of System Dynamics

#### 2.2.1 Ergometer dynamics

The ergometer is modeled as a damped flywheel, with the input force taken as an applied torque proportional to the motive force applied by the rower. For a flywheel with moment of inertia $I$, angular velocity $\omega$, and damping coefficient c, an analysis of the angular momentum gives the following relationship for the acceleration of the flywheel:

$$I\frac{d\omega}{dt} = T - c\omega \tag{1}$$

As no data was available for the mass, the moment of inertia, and damping factor of the ergometer flywheel, the values were fitted to match the Fédération Internationale des Sociétés d'Aviron (FISA) regulations for a coxless four with an 80 kg crew, which is agreed by competitive rowers to be the calibration standard for the concept 2 indoor rower [6]. For both the boat and the rowing machine, the rower is taken as rowing at a rate of 30 strokes/min with a power stroke : recovery ratio of 2:1. The power input is taken from the experimental data of Martin [2] and is shown as the solid line in Figure 5. Equation 1 is integrated numerically for 20 cycles. The simulation was found to reach steady state after 10 cycles and cycle number 16 was used for the comparison.

#### 2.2.2 Dynamics of the sculling boat

The single scull is a more complex system, as the hull is subject to skin friction drag, form drag, and wave drag [7]. The sculler is assumed to be rowing on flat water with no wind, hence external factors, such as waves and headwinds, will not be considered. As the sculler sits on a sliding seat, which moves as he rows, the centre of mass of the system is constantly changing. For the purposes of the model, skin friction and form drag are lumped together. At racing speeds, single sculls travel at an average speed of just over 16 km/h or 4.44 m/s, which translates to a hull Froude number of 0.52. The critical Froude number of 0.54, which corresponds to a maximum in the wave drag resistance curve, translates to a velocity of 16.54 km/h or 4.6 m/s. The conservation of momentum for the system yields:

$$\frac{d}{dt}(M_B V_B + M_R(V_B + V_R)) = F - k_{SF} V_B - k_{WD} V_B \qquad (2)$$

where $M_B$ is the mass of the boat, $M_R$ is the mass of the rower, $V_B$ is the boat velocity, $k_{SF}$ is the skin friction and form drag coefficient (constant), $k_{WD}$ is the wave drag coefficient (dependent on $V_B$), and $V_R$ is the velocity of the rower relative to the boat. In reality, the drag factor will vary slightly between the power stroke and the recovery due to the buoyancy of the blade in the water during the power stroke and the effect of the blade pitch, which generates a vertical force during the stroke. For most rowers, the pitch is set at an angle between 2 and 6° (typically 4°) [8], translating to a vertical force of between 3.5 and 10% of the total effort. This effect causes the boat to sit higher in the water, with less wetted area and hence less skin friction drag during the power stroke, and to sit lower in the water during the recovery. Rowing shells have a fine entry and after run, increasing the waterline during the recovery although the reduction in wave drag will not entirely compensate for the increase in skin friction drag.

In contrast to the ergometer, the movement of the rower's body and position of the rower's hands has a significant effect on the movement of the boat relative to the rower, as well as on the angle of the driving force exerted by the sculls on the water. Hence the footrest (stretcher) was taken as the fixed point for the model, and the positions of the hands and the centers of gravity of the lower legs (shanks), thighs, and hips relative to this point were calculated from the ankle angle and knee angle [2] using segment lengths and centers of gravity from tables of standard anthropomorphic data for males [5]. As no data was given in Martin's study on hip angles, the hip angles given by Upson [3] at the catch and finish on the same ergometer model were used, and hip angles were assumed to vary smoothly between these limits. The arms are taken to be outstretched during the initial 70% of the drive, and for the final 30% of the drive and the first 30% of the recovery, they are taken to be flexing to bring the handles of the sculls to the chest. The net momentum of the system is therefore taken as the sum of the momentum of the boat, and the feet, shanks, thighs, torso, head, and arms of the rower. The velocity of the individual components is calculated from the position relative to the stretcher, as shown schematically in Figure 6. Hence the net momentum of the rower relative to the boat is given as:

$$M_R V_R = 2M_S V_S + 2M_T V_T + M_{TH} V_{TH} + 2M_A V_A \qquad (3)$$

where $M$ represents the mass, $V$ represents velocity relative to the stretcher, and the subscripts denote the shank (S), thigh (T), torso and head (TH), and arm (A). The feet are not included in the calculation as they are fixed to the stretcher, and hence any movement of their centre of gravity relative to the boat is considered negligible. The angle of the scull to the direction of motion is calculated from the position of the hands. For the purpose of comparison, the motive force for the boat (the dashed line in Figure 5) uses the same values, adjusted to account for the changing angle of application of force, and the change in momentum of the entire system (boat and sculler) are calculated from Equation 2. The mass of the rower is taken to be 80 kg and the rower's height to be 1.8 m. The mass of the boat is 14 kg, as set by FISA standards [9]. Equations 2 and 3 were used to calculate the net momentum of the boat and the sculler, as well as the boat speed relative to the water ($V_B$).

## 3. RESULTS

The results for the original model are shown in Figure 7. The velocity for the ergometer is higher because of the calibration to a faster boat (the 2-km world championship winning time in 2007 for a coxless 4 is approximately 50 s less than

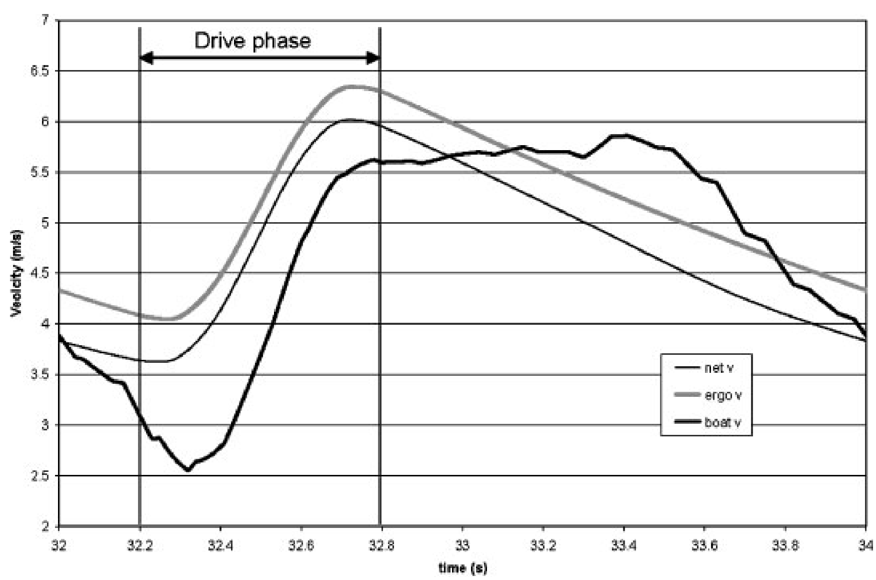


**Figure 7.** Variation in velocity during the stroke cycle for the ergometer, system centre of gravity (net v, in black), and the boat.

  

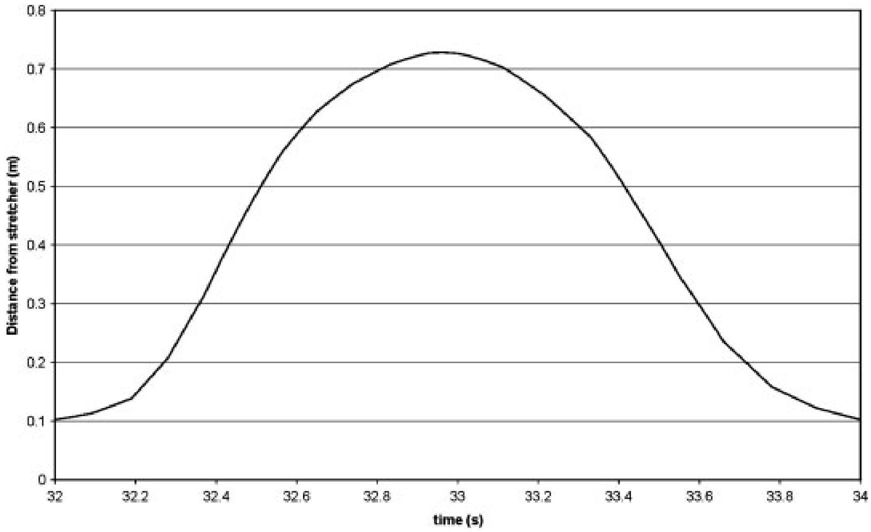


**Figure 8.** Position of the rower's centre of gravity relative to the foot rest, throughout the 16th cycle of the simulation.

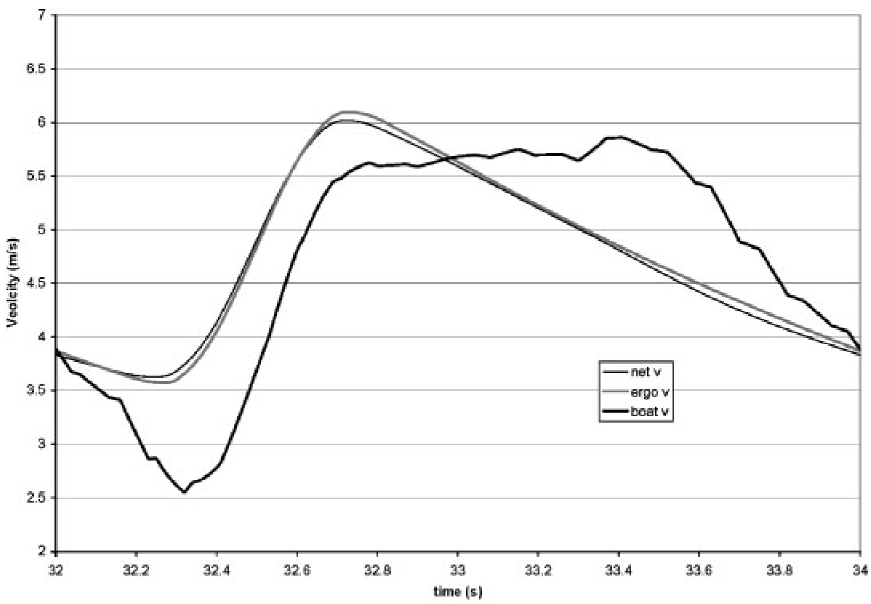


**Figure 9.** Variation in velocity for boat and ergometer with matched average velocity.

that for a single scull) [10]. The shape of the curve for the ergometer velocity and the net velocity are similar, however. The velocity of the boat varies considerably from the net velocity, which can be attributed to the effect of the motion of the rower during the cycle (Figure 8). The same graph is shown in Figure 9, with the ergometer mean velocity calculation adjusted to match that of the rower on the water. It is of interest that the velocity range for the ergometer flywheel is larger than that for on-water rowing, indicating that the overall effect of momentum is lower. The variation seen in the boat velocity (bold line) is an artifact due to the use of interpolation in the calculation of segment positions and hence velocities.

The graph of drag against time (Figure 10) shows that the drag forces on the boat and the ergometer vary considerably, particularly during the recovery phase. The drag is constant towards the end of the recovery, due to the constant boat speed, induced by the rower's movement towards the stern of the boat.

## 4. CONCLUSION

The results show that the dynamics of the rowing machine and the calibration of the performance monitor provide an acceptable simulation of the overall dynamics of the boat and the rower, testifying to the efforts of the designers in producing an effective training tool for competitive rowers. However, the dynamic model of the boat's movement also shows the differences between the two systems. The observed boat speed of competitive rowers are closely matched, as shown in Figures 7 and 9 [11]; the boat accelerates slightly as the rower moves

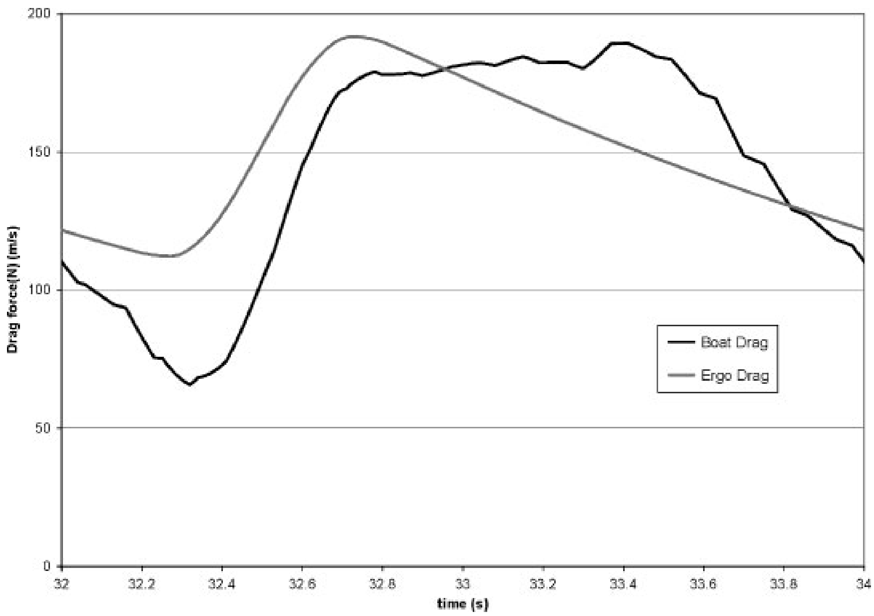


**Figure 10.** Drag forces on the boat and the ergometer (resisting motion).

backwards to the catch position on the slide, and decelerates noticeably as the blades enter the water and the rower changes direction. The model shows that this 'check' at the catch is largely due to the change in direction of the movement of the rower's body, rather than being caused by the entry of the blades of the oar into the water, which is modeled as totally efficient. The boat is moving more slowly than the rower during the drive phase, which is to be expected because of the motion of the sliding seat. The sensitivity of the boat velocity to the movement of the rower during the recovery reflects the importance placed on letting the boat run, and on smooth technique, in the sport of rowing. The movement of the rower during the recovery will not, however, have any effect on the ergometer.

Additionally, the depth of the oar in the water and the angle of the blade face at the catch, which have an enormous impact on the speed of the boat, are not simulated by the rowing machine, and it can be concluded that bad technique is not punished by the machine. Rowers will say that ergometers do not float; there is only so much that an ergometer can measure, and the ergometer is primarily used as a tool to gauge the rower's physical condition, rather than as an absolute predictor of performance. The manufacturer of RowPerfect claims to address this shortcoming, and will simulate the dynamics more closely at the catch, but will still not really penalize poor technique in the same way as on the water.

As with the ergometer, the model is limited by the assumptions made. The pitching caused by the rower's movement is not considered, and the lift on the boat due to the buoyancy of the oars and the slight positive pitch of between 2° and 6° used on the blades [7], which reduces the drag on the boat during the drive phase, is similarly omitted. These factors will be considered in further research.

The model shows that the use of viscous damping on the vanes of the flywheel of the concept 2 indoor rower is a valid analog for boat resistance, as the long and narrow hull form of rowing shells does not create a large amount of wave and form drag, with skin friction drag forming the dominant component. The concept 2 rower therefore provides a more accurate simulation of the rowing action than other indoor rowers using a friction brake or springs to provide the resistance to motion. It should be noted that the viscous nature of resistance also makes the indoor rower suitable principally for conditioning and anaerobic threshold training, rather than strength training.

As the indoor rower does not punish poor technique, it can also be concluded that it can only be an adjunct to on-water training or for maintaining physical condition. The rowing adage that 'mileage makes champions' holds true.

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