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Development of a kayak race prediction including environmental and athlete effects

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Abstract

The aim of this study is to produce a simulator for sprint kayak racing which would allow the prediction of race times based on the physiological capabilities and mass of a given athlete. The simulator has been verified using established empirical data for the prediction of environmental effects and has been shown to be accurate, however verification of the physiological model is difficult to do by using general race data. An investigation into the fatigue model which has been implemented shows that further investigation is required to calibrate the simulator and produce more accurate results over a variety of distances. However, the simulator does show quite how sensitive the selection of appropriate level of effort is to the final race time for the 1000m.

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1. Introduction

Sprint Kayak and Canoe events take place on a straight course on typically a wide expanse of water. The events are usually for a set of boats that commence from a standing start within their own delineated lanes. The purpose of the crew is to ensure that at any time during the race they are propelling the craft with the an appropriate effort such that they rapidly accelerate the craft to an appropriate speed, modify their stroke rate during the race and if deemed necessary respond to the efforts of the other crews such that they finish first. What is not clear is what is the most appropriate race strategy for a particular combination of crew and boat type for a given set of environmental conditions. One of the dangers is that the crew overexerts itself too early in the race such that later on they have insufficient reserves to respond to the efforts of other crews. Similarly that the perceived psychological benefit of being in front outweighs a more cautious strategy that attempts to manage crew effort.

The performance of the boat and crew will depend on a wide variety of factors. For instance the design of the equipment used, boats and paddles primarily, are governed by the individual event/sports rules and regulations

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Fig. 1: Six degrees of freedom.

whereas, within certain constraints, the environmental effects of the winds strength, direction and variability, and resultant wind generated waves will all have an influence on the actual speed obtained by the participants. In this work a visual Matlab-Simulink based environment has been developed that allows a whole race to be simulated with multiple competitors. Appropriate Naval Architecture tools for the prediction of the performance of the boat in terms of its displacement, surface area, form and wave drag have been used for the resistance model with additional modelling applied for the influence of wind and waves on speed loss [6]. The crew members themselves are represented in terms of their mass and a model for the developed thrust of their individual stroke alongside a model for the maximum total and sustained effort [2].

2. RaceSim Development

2.1. Model Structure

The approach for the time-step simulation follows naval architecture practice for ship powering, manoeuvring and sea keepin [6]. The six degrees of freedom shown in Figure 1 can be reduced when considering powering alone to a balance of forces which establishes a mean drift, a fluctuating surge velocity and a model that captures the additional resistance components due to drift, added resistance in waves due to pitch, roll and heave, alongside wind loading. In this model the primary unsteadiness is due to the periodic impulse of the paddle action. The paddler is assumed to control the straight ahead motion through appropriate compensation left and right on opposing strokes.

Propulsive force, P, is entered as a function of time, and resistance is calculated based on a number of conditions including the speed, angle of drift, and size of the athlete. The net force is then used to calculate the acceleration of the kayak using Newtons Second Law of Motion where the effective mass includes that added due to the acceleration of the water. Both the kayak and athlete are assumed to be rigid bodies, and the force is being applied at the centre of mass of the kayak and athlete combined, reducing the model to 2 degrees of freedom in surge (x) and sway (y).

The acceleration was calculated by combining all of the resistance components and the propulsion model, to find a net force. The mass of the athlete and all equipment was then combined with the added mass of the kayak. The added mass is dependent on the projected area of the kayak in the water and so was calculated using an ellipsoid approximation for the submerged part of the hull, with formulae from [8]. The geometry is based on that of a representative competition kayak such that it's projected and surface area are known for different displacements, based on the mass of the athlete and equipment. The qualitative representation of the forces involved is,

$$(M + M_a)\,\ddot{x} \quad = \quad P(t) - \Big[\quad (1 + C_{aw}) \sum R_{hydro} \quad + \quad R_{aero} \quad \Big], \tag{1}$$

where $M + M_a$ is the mass plus added mass of the system, $\ddot{x}$ is the acceleration, P is the propulsive force as a function of time, t, C_{aw} is the coefficient of resistance added due to waves, including the effect of pitch roll and heave, $\sum R_{hydro}$ is the sum of the hydrodynamic resistance components and R_{aero} is the aerodynamic resistance. Once the acceleration is known it can be integrated to find the speed at the end of that time step, and integrated again to find the distance covered in that time step. Simulink uses an adaptive time step so that areas of the model which are changing rapidly have a smaller time step and higher accuracy, and more constant areas have a longer time step and therefore are less computationally expensive. This simulation uses the ODE45 solver and the time step is typically of order 0.001 seconds.

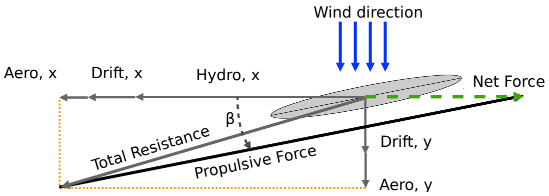


Fig. 2: Breakdown of force vectors. Note that the y component of the drift force

2.2. Resistance Model

The hydrodynamic resistance is calculated using

$$R_{hydro} = \frac{1}{2}\rho\dot{x}^2 S\left[(1+k)\,C_f + C_w + C_\beta\right] \tag{2}$$

Where ρ is the density of fresh water, $1000kg/m^3$, S is the wetted surface area, C_w is the wave making resistance coefficient, C_β is the resistance coefficient due to the angle of drift, and where,

$$(1+k) = 2.76\left(\frac{L}{\nabla^{\frac{1}{3}}}\right)^{-0.4}, \quad C_f = \frac{0.075}{(\log_{10} Re - 2)^2}, \quad Re = \frac{\dot{x}L}{\nu}.$$

C_f is calculated using the ITTC '57 correlation line and is dependent on the Reynolds number, Re of the kayak, where ν is the kinematic viscosity of water as a function of temperature, L is the boat length [6]. The form factor, $(1+k)$ is dependent on ∇, the volumetric displacement [6]. The wave making resistance coefficient, C_w, was predicted for different draughts and speeds using a potential flow method known as 'thin ship theory', based on the 3D geometry of a kayak shell [2].

This model also take into account the effect of environmental conditions. Wind produces waves on the water surface as well as providing a lateral force which would require the athlete to maintain an angle of drift, β, to keep the net force production, and therefore the direction of travel, in the direction of the race course as shown in Figure 2. In the hydrodynamic model, the waves are accounted for by using the fetch of water between the edge of the lake and the centre of the kayak. Empirical formulae are used to calculate the surface wave characteristics [9], the added resistance factor due to these waves, C_{aw} [10], and the additional resistance due to the angle of drift, which gives the resulting force in two components, in-line with the direction of travel, x, and perpendicular to that direction, y [4]. The coefficient in the x direction, C_β is used in the hydrodynamic resistance while the y helps balance the lateral forces.

The aerodynamic resistance is calculated using

$$R_{aero} = \frac{1}{2}\rho_a\dot{x}^2 S_a C_a \tag{3}$$

where S_a is the projected area of the kayak and athlete, estimated using their height and gender according to an anthropometric database [7]. The air density, ρ_a is a function of temperature. The drag coefficient, C_a, is assumed to be similar to that of an ellipse to represent the athlete's torso and arms as well as the tumblehome on the kayak [8].

2.3. Propulsion Model

The propulsion model uses a non-dimensionalised force profile which represents a single paddle stroke, followed by a small period of no force as the one blade leaves the water before the other enters. A number of studies have been done using strain gauges to measure the force directly from the kayak paddle, either for measurement on the water or when using a kayak ergo-meter which uses a fly wheel and fan to replicate the resistance of a kayak blade in the water. Figure 3 shows the force measured from the paddle on an ergo-meter [5].

By using a non-dimensionalised force profile with a unit magnitude and period, the model can be easily scaled to represent different athletes physical abilities such as peak power and fatigue rate. Figure 4 shows the comparison of

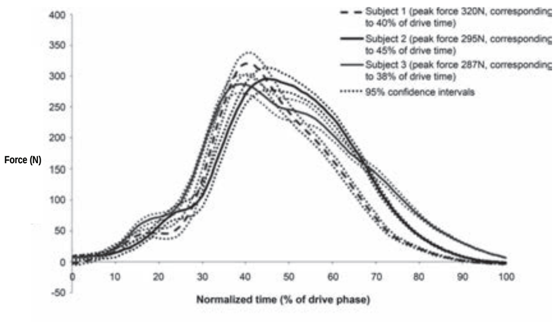


Fig. 3: Force profiles of elite kayakers [5],

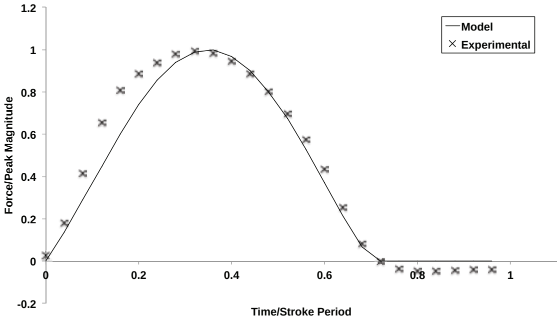


Fig. 4: Comparison of non-dimensionalised, measured and modelled propulsive force.

a sinusoidal force profile with the non-dimensionalised on-water measurement of an elite paddler, and it can be seen that the sinusoidal profile reasonably matches the measured one. The first 70% represents the drive phase, with the paddle submerged and the last 30% shows the transition phase where both blades are in the air before the next stroke period begins. The shape of this profile will vary depending on the paddler's technical proficiency and so the impulse per stroke is the focus of this model. The increase in force early in the measurement is due to the high entrance speed into the water, and the negative values in the transition phase are caused by the aerodynamic drag of the blade.

The magnitude of the peak force in each stroke is controlled by a decay function which represents the fatigue experienced by the athlete during the race. The fatigue model is split into two major systems, anaerobic and aerobic, with the anaerobic system split further into two types, alactic and lactic work. Alactic work can be sustained for a few seconds and provides peak power with a sharp decrease in output. Lactic work can be sustained slightly longer but still with a relatively sharp drop in power output, before the athlete is left using aerobically produced energy [1].

These functions give the force delivered by the athlete to the paddle, but the efficiency of the blade will determine how much force is effective in driving the kayak. Formulae for the efficiency of two different stroke techniques, the drag technique and lift technique, has been derived by considering their swept area and vortex generation [3]. Elite kayakers use a wing shaped blade, and a sweeping technique to generate lift as well as drag forces on the blade.

3. Parametric Study Results and Coaching Applications

Initial testing of the simulator can be seen in Figure 5, showing the acceleration phase of a race, through to the steady speed phase over the first 100m. The model was developed to allow it to be used as a potential training tool, to be used by coaches and athletes who are not necessarily experienced matlab users. To make the simulator more useful it was developed to allow the parametric study of individual parameters. These included investigations from a physiological perspective, looking at the effect of different technique and tactical aspects, and predicting the effects of environmental conditions. To allow an ease of communication with the coaches and athletes, the studies were set up in Simulink's integrated virtual reality environment, which allows races to be simulated between 9 competitors, giving a real time representation of the race. These races record the 50m split times of each competitor, a common metric used by coaches, as well as visually showing the progression of the race as different parameters start to affect the performance of each competitor.

The finish line throw was investigated to try and establish the ideal timing of the throw to achieve the best time for the race. At the end of most sprinting events, in a number of different sports, the athletes can be seen lunging for the line. The advantage is that with a well timed through the centre of mass of the kayak and paddler doesn't have to travel the full race distance. The timing of this throw is incredibly important as it involves the athletes throwing their legs forward with the kayak, while their upper body rotates to an almost flat position on the deck. Once in this position it is impossible to propel the kayak effectively using the paddle so the speed of the kayak drops very quickly, and mis-timing this throw can actually result in a worse finishing position than not throwing at all. Figure 6 show the comparison of four otherwise identical athletes in a race, 3 of them throw the kayak forwards at 2m, 6m and 11m from

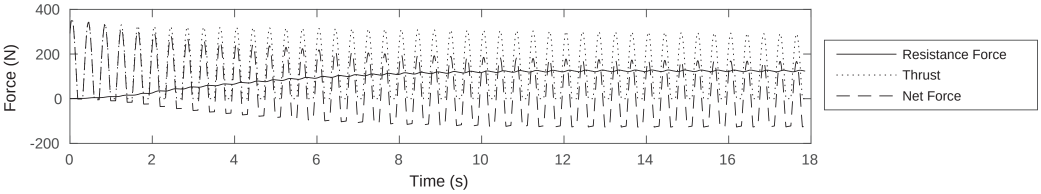


Fig. 5: 100m race simulation. The initial acceleration phase can be seen in the first 10 seconds. Resistance is proportional to the speed squared so as the speed increases, so does the resistance, with the periodic thrust being seen as small surge fluctuations in resistance force.

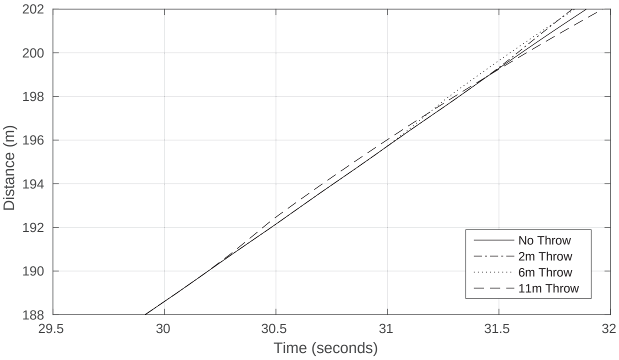


Fig. 6: Finish line throw comparing the distance from the finish line the throw was executed for a 200m race.

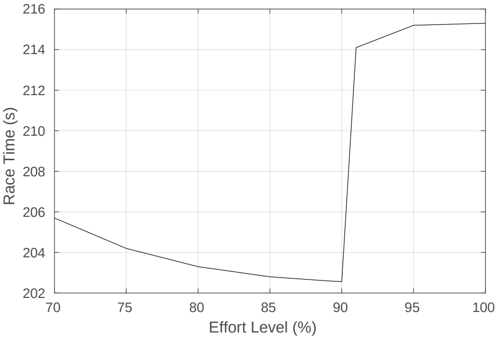


Fig. 7: Fatigue model investigation.

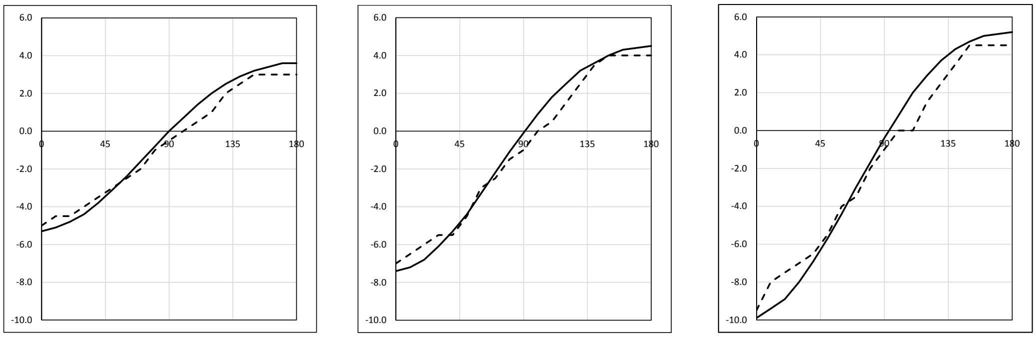
the line and the figure shows their distance plotted against time. It can be seen that the athlete who threw 6m from the line won, the one who threw at 2m came second, but the one who did not throw came third, still beating the athlete who threw at 11m.

The sensitivity of the mass and size of the athlete to the speed of the race was investigated. Sprint events are not usually mass sensitive in sports where the competitors are pushing solely through the air, because an increase in mass usually represents a very small increase in profile area and therefore aerodynamic drag. In water however the density of the fluid is so much higher that the resistance is more sensitive to increases in mass and therefore surface area.

Table 1: Comparison of simulated races with results from London 2012.

Event	Mens K-1 200m	Mens K-1 1000m	Mens K-2 200m
Simulator Time (*s*)	31.36	202.56	30.35
Actual Time (*s*)	36.25	214.83	34.42
Variance (*s*)	4.89	12.27	4.07
Percentage Variance (%)	13.48	5.71	11.83

The fatigue model was investigated by comparing simulated races of different lengths, in the K-1 and K-2 category against the results from the London Olympics in 2012. Table 1 shows the results of these simulations and uses a percentage variance to quantify the accuracy of the model. It can be seen that the simulator is predicting slightly fast race times, reflecting the uncertainty in the actual environmental conditions and the kayak and athlete. The fatigue model allows the user to input the effective effort of the athlete as a percentage of their peak power, Figure 7 shows the effect this has on finishing time. In this simulation, the alactic threshold was assumed to be 90% of the peak power, and it can be seen that staying below this threshold yields a significantly quicker time over the course. Calibration of this model could be achieved by running a standard series of tests on a subject to determine their peak, alactic and lactic threshold powers, and timed on water efforts.



(a) 1.5 ms^{-1} (b) 2.0 ms^{-1} (c) 2.5 ms^{-1}

Fig. 8: Time correction in seconds plotted against wind direction in degrees, where 0 is a head wind and 180 is a tailwind, plotted at different wind speeds. Dotted lines show empirical values and solid lines show the prediction from the simulator.

The effect of wind on the race time for a 1000m K1 event was investigated using the simulator. Wind angles from directly ahead to directly behind were investigated to predict their effect on the total race time and compared against an available set of empirical data collated from various events. Figures 8a, 8b and 8c show the comparison between the two data sets. It can be seen that the prediction of the simulator agrees well with the empirically collected data, but there are some differences with high speed cross winds. It should be noted that the empirical data is accurate to 0.5 seconds, so when the time difference is in the order of 1 second the results are difficult to compare.

4. Conclusions

Empirical studies have already been conducted into the effect of the weather on race times, and has been used to verify the simulator, and shows a high level of accuracy. Other elements of the simulator are hard to verify, however, due to the lack of data available with regard to the physiology of the athlete or the technique being used.

In its current form the simulator would be used as a useful tool whilst recruiting athletes by recording their race times at particular events and producing an effective "calm weather" time. It could also neutralise the problem of training in adverse conditions which often makes it difficult to determine how well an athlete is performing compared to their historical data, or to set accurate training goals in these conditions.

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