

The Influence of Paddle Orientation on Boat Velocity in Canoeing

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Abstract. The orientation of the paddle during the outrigger canoe stroke is an important factor in maximising propulsive forces. In order to investigate the influence of paddle orientation on boat velocity, a mathematical model of the outrigger canoe paddling stroke was established. The model accounted for the movement of the paddler within the boat, the motions of the paddle blade through the water, generating fluid forces, and the resistive forces acting on the boat and paddler. The model was validated against on water data for an elite female paddler, with a difference of only 1.3% between model output and measured on water data being found. Simulations were carried out to determine the influence of the paddle blade offset angle relative to the shaft. Maximum velocity was achieved in the condition where the paddle's angle of attack was closest to zero when peak paddle velocity occurred. This was found to be at an offset angle of -20 degrees between the shaft and blade of the paddle. For the paddler investigated here, the model outputs suggested that using a normal paddle with no offset angle between the paddle blade and shaft may not be optimal.

Keywords: Outrigger canoe, paddle, drag force, propulsion, model

1. Introduction

Canoe paddling involves a paddler, either individually or as part of a larger crew, propelling the boat forwards, using a single paddle. The paddle is held with one hand at the top of the shaft and the other lower on the shaft, near the top of the paddle blade. Different forms of flat water canoeing are seen with disciplines such as dragon boat paddling, Canadian canoeing and outrigger canoeing. There are differences in the technique used in each of these, due in part to the design of the boat. However, the same propulsive mechanisms will contribute to boat motion.

The canoe paddling stroke can be split into a drive phase and a recovery phase. The stroke involves the paddler leaning forwards with the trunk, reaching forwards with their hands, to enter the paddle blade deep into the water (paddle entry). A fluid force is then generated in the direction of boat motion during the drive phase by the paddler extending their trunk and pulling the paddle backwards through the water with their arms. This propulsive fluid force acts to overcome the drag forces acting on the boat and paddler in order to accelerate the boat. At the end of the drive phase, the paddle is extracted from the water (paddle exit) to mark the transition between the drive and recovery phases. During the recovery phase, the paddler moves their shoulders, arms and paddle forwards ready for the next stroke.

The key performance criterion in flat water canoe racing is race time, which can be reduced through an increase in mean horizontal boat velocity. Humphries et al. [1] found high correlations between force output on a canoe ergometer and 250 m race time, as well as finding similar correlations against race time for a range of anthropometric characteristics. Standon et al. [2] investigated the role of stroke rate in determining paddling performance, suggesting that stroke rate has an important influence on the rate of force development. Although these studies make a valuable contribution to our understanding of what contributes to canoe paddling performance, they are specific to tethered canoe and ergometer paddling.

Ho et al. [3] recently investigated differences between elite and sub-elite dragon boat paddlers in untethered open water paddling. They found that the elite paddlers produced higher peak and average paddle

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forces than the sub-elite group. This supported the findings of Caplan [4] who showed, using a sensitivity analysis, that increasing the velocity of the paddle backwards through the water had the greatest effect on boat velocity, compared to other variables examined, such as the fluid dynamic properties of the paddle (including paddle area), the magnitude of paddler movement in the boat, boat and paddler masses, and the duration of the recovery phase. Such an increase in paddle velocity would increase the paddle force due to the fluid dynamic interaction between the paddle blade and water. Ho et al. [3] also showed that the elite group maintained a more vertical paddle orientation throughout the drive phase.

The aim of this study was to further investigate the role of paddle orientation through the drive phase of the stroke on horizontal boat velocity, by developing a mathematical model of paddling an O1 flat water outrigger canoe, which could be used to determine the influence of changing the paddle blade angular offset with the shaft. The O1 outrigger canoe is used by the British Dragon Boat Racing Association as an individual training craft and for national trials. The O1 is a modified K1 kayak hull that has an outrigger attached to one side.

2. Model development

According to Newton's second law, a linear force, F , generated by a system can be given by

$$\sum F = ma \quad (1)$$

where m is the mass of the system and a is its acceleration. If input forces and masses of a system are known, then the velocity, V , of that system can be calculated as the integral of the system acceleration, such that

$$V = \int a dt \quad (2)$$

In the case of the canoe stroke, equation (1) can be further developed, giving

$$P - D = m \frac{dv_{boat}}{dt} + M \left(\frac{dv_{crew}}{dt} + \frac{dv_{boat}}{dt} \right) \quad (3)$$

where P is the total propulsive force, D is the total drag force, m is the mass of the boat, M is the combined mass of the boat, paddlers and paddles, v_{boat} is the horizontal velocity of the boat relative to the earth and v_{crew} is the horizontal velocity of the paddler's centre of mass relative to the boat. Similar models have been presented previously for rowing (e.g. [7]). As the lower body remains almost stationary relative to the boat through the stroke, it was assumed that only movements of the upper body influenced boat velocity.

In order to determine the propulsive force at the paddle, the fluid dynamic properties of the paddle blade and the kinematics of the paddle through the stroke were modelled. The paddle will generate both a lift and a drag force. However, it was assumed that the paddle shaft only moves in the sagittal plane, so the lift forces generated will be vertical. Thus it was assumed that only drag forces contribute to horizontal propulsion. Any lift forces would act to lift the boat out of the water early in the stroke and lower the boat late in the stroke. Although this would influence the resistive forces acting on the boat, by changing the wetted surface area, it was assumed that the opposing influences of lift early and late in the stroke will result in a negligible overall effect on boat velocity. The drag force at the paddle was given by

$$F_D = \frac{1}{2} \rho C_D A v_{p-rel}^2 \quad (4)$$

where ρ is the fluid density, A is the projected area of the paddle, v_{p-rel} is the relative velocity between the paddle and water and C_D is a dimensionless drag force coefficient that will depend on the angle of attack between the paddle and oncoming fluid flow, and the design of the paddle [7].

Assuming that the boat is being paddled on calm, flat water, the relative velocity, v_{p-rel} , between the paddle and water was then given by

$$v_{p-rel} = v_{boat} - v_{paddle} \quad (5)$$

where v_{paddle} is the velocity of the paddle relative to the boat. This velocity was measured from video data, as described in Section 3.

Sumner et al. [5] presented drag coefficients for a range of paddles held static at a range of angles of attack in a wind tunnel. It was shown that the drag coefficient, C_D , could be modelled by

$$C_D = C_{D0} \cos \alpha \quad (6)$$

where C_{D0} is the drag coefficient at an angle of attack, α , of zero degrees, or when the direction of fluid flow is perpendicular to the face of the paddle. The angle of attack, α , was taken from the measured relationship for the paddle orientation with respect to the water through the stroke (see Section 3).

During each stroke, the location of the paddler's upper body centre of mass will oscillate back and forth. In a similar way as has been carried out previously for rowing [6-7] this movement was modelled as a single mass moving as half of a cosine function of time in each phase of the stroke, although the direction of motion was opposite to that seen for rowing in each phase of the stroke. The position of the paddler's upper body centre of mass during the drive phase, x_1 , was modelled as

$$x_1 = a \cos \frac{\pi t}{\tau_1} \quad (7)$$

where a is the amplitude of the paddler movements back and forth in the boat, τ_1 is the drive phase duration and $0 \leq t \leq \tau_1$. During the recovery phase this relationship changed such that the upper body centre of mass position of the paddler, x_2 , was given by

$$x_2 = -a \cos \frac{\pi t}{\tau_2} \quad (8)$$

where τ_2 is the duration of the recovery phase, and $\tau_1 \leq t \leq \tau_1 + \tau_2$. The upper body centre of mass position of the paddler throughout the stroke was then differentiated to give the velocity of the upper body centre of mass, such that,

$$v_{crew} = \dot{x}_1 \quad (9)$$

and

$$v_{crew} = \dot{x}_2 \quad (10)$$

during the drive and recovery phases of the stroke, respectively.

Finally, the drag forces acting on the boat and paddler were calculated. For the purposes of this study measured data, as discussed in the next section, were taken from an elite dragon boat paddler in an O1 flat water training craft. The O1 single paddler outrigger canoe uses the same hull as a K1 kayak. Although no drag data were available for the O1, data were presented by Dansprint ApS [8] for a K1 with an added paddler mass of 50 kg, similar to the mass of the paddler used here for the model validation. From these data, the hydrodynamic drag, D_{hydro} , acting on the boat was given by

$$D_{hydro} = 3.2754v_{boat}^2 - 2.3536v_{boat} \quad (11)$$

The aerodynamic drag, D_{aero} , acting on the surfaces of the boat above the waterline and the paddler, was assumed to be modelled by the relationship presented by Hoerner [9] for a seated man [7, 10-11] such that

$$D_{aero} = n(0.3484v_{boat}^2) \quad (12)$$

where n is the number of paddlers in the boat. The total drag, D , was then the sum of the aerodynamic and hydrodynamic drag forces.

3. On-water data collection

3.1. Subject

One female elite dragon boat paddler was filmed during a single on-water trial to determine the kinematics of the paddle and paddler during the stroke. The paddler fully consented to be filmed during this session. The paddler had a body mass of 52 kg and a height of 1.58 m. A few days before the on-water filming trial, the paddler also competed in the national squad world championship trials, completing a 500m race distance in 175 s, equating to a mean horizontal boat velocity of 2.86 m s^{-1} . This velocity was used in order to validate the model. During both the on-water filming session and the national trials, the paddler

used the same O1 outrigger canoe.

3.2. Motion analysis methods

In order to determine the amplitude of paddler motion back and forth in the boat, the paddler was filmed from a lateral view by a miniDV camera (HDR-AV1, Sony, Japan) which was positioned on the shore. The frame rate of the camera was 50 Hz and the shutter speed was set at $1/1000^{\text{th}}$ second. The filming session took place on calm water, and light conditions were very good. Scale points on the boat indicated a horizontal distance of 1m. A 7 point, 6 segment spatial model was used for the upper body, with an additional 2 points used to define the upper and lower limits of the paddle shaft (Figure 1). Markers were placed on the right hip, right shoulder, right elbow, right wrist, left shoulder, left elbow and left wrist. As the seat and feet were fixed in the boat, motion of the lower body relative to the boat was assumed to be zero.

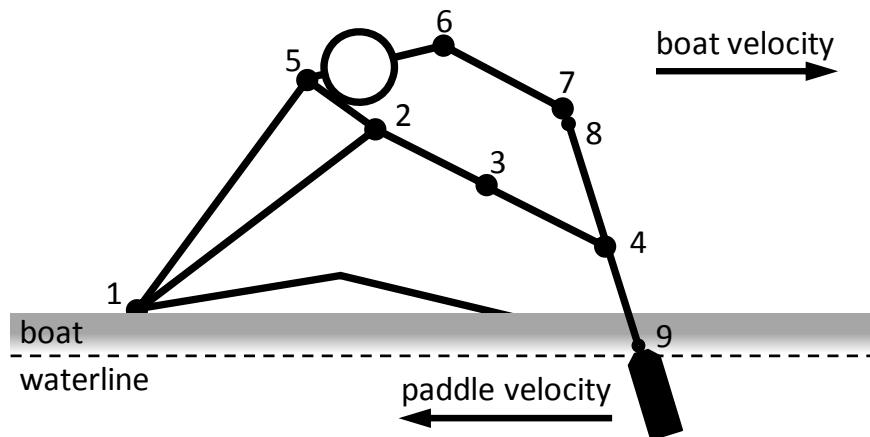


Fig. 1: Spatial model of the paddler, showing the marker set used to determine stroke kinematics during on-water paddling. Markers were placed on the right hip (1), shoulder (2), elbow (3) and wrist (4), left shoulder (5), elbow (6) and wrist (7), and at the top (8) and bottom (9) of the paddle shaft.

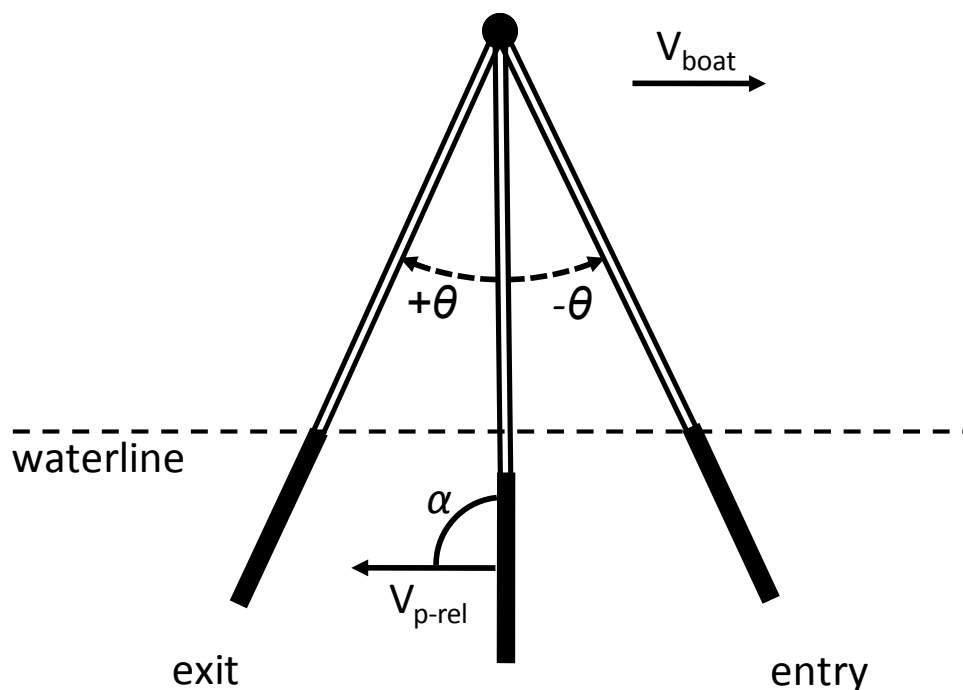


Fig. 2: Side view of the paddle, illustrating the directions of positive and negative angular paddle displacements (θ) in relation to the entry and exit time points of the stroke, the direction of relative paddle velocity with respect to the water ($V_{p\text{-rel}}$), and the angle of attack (α) that this velocity makes with the chord of the paddle blade.

The video data were manually digitized using Vicon Motus software (Motus 9.0, Vicon Motion Systems,

Oxford). The percentage mass of each segment with respect to total body mass, and the centre of mass location for each segment were defined according to Winter [12], and the centre of mass coordinates determined automatically using Vicon Motus. Only the horizontal oscillations of the centre of mass were needed for the model as any vertical movements were assumed not to contribute to propulsion.

In order to calculate the propulsive forces generated by the paddle that contribute to modelled boat velocity, both the velocity of the paddle relative to the boat and the orientation of the paddle were determined. It was assumed that the centre of pressure acting on the paddle blade was halfway from the shaft to the tip. As the paddle blade was submerged through the stroke, the centre of pressure location was extrapolated from the two paddle marker coordinates, based on the known dimensions of the paddle. The orientation of the paddle was calculated from the angle made between the paddle shaft and a vertical reference line (Figure 2). The blade entry and exit points were defined as when the paddle entered and exited the water, respectively.

3.3. Motion analysis results

Stroke rate was observed to be $76.9 \text{ strokes min}^{-1}$. The durations of the drive and recovery phases were 0.4 s and 0.38 s, respectively.

Figure 3 illustrates the change in paddle orientation through the paddle stroke. Paddle entry and exit points are indicated and the data demonstrated that the paddle angle had an almost linear relationship with time through the drive phase. Paddle angle at entry was -27 degrees and increased to 50 degrees at exit.

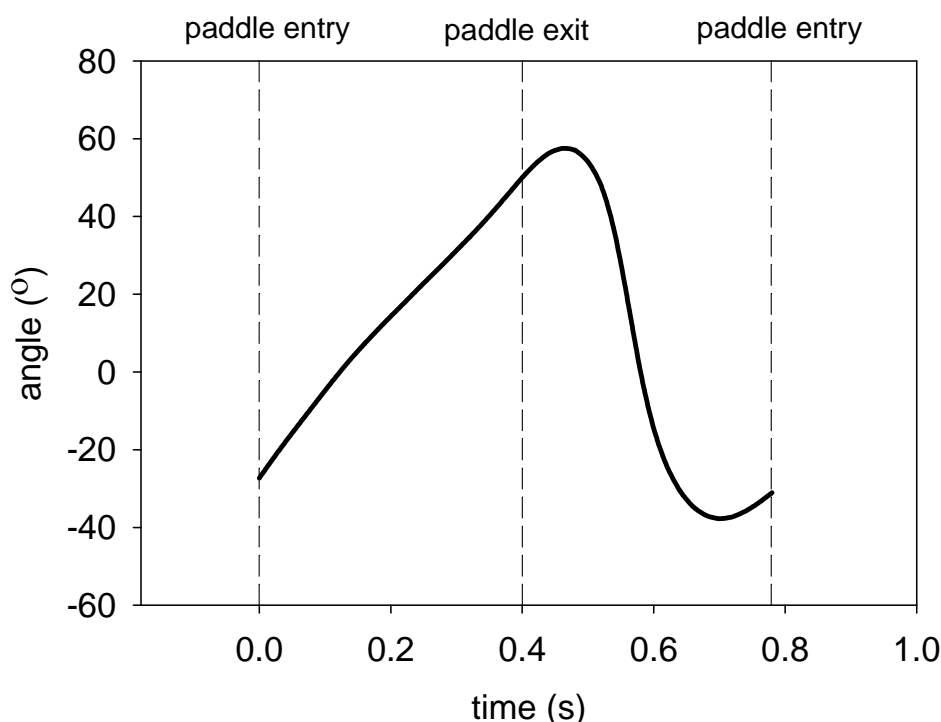


Fig. 3: Paddle angle is shown over one complete paddle stroke. Paddle entry and exit points are indicated by vertical dashed lines. During the drive phase, an almost linear increase in paddle angle over time was seen.

Paddle horizontal velocity relative to the boat was seen to be approximately zero at the start of the drive phase (Figure 4). It subsequently increased (negatively due to being in the opposite direction to boat velocity) to -4.13 m s^{-1} at a corresponding paddle angle of 14 degrees, before approaching a velocity of -0.98 m s^{-1} at paddle exit.

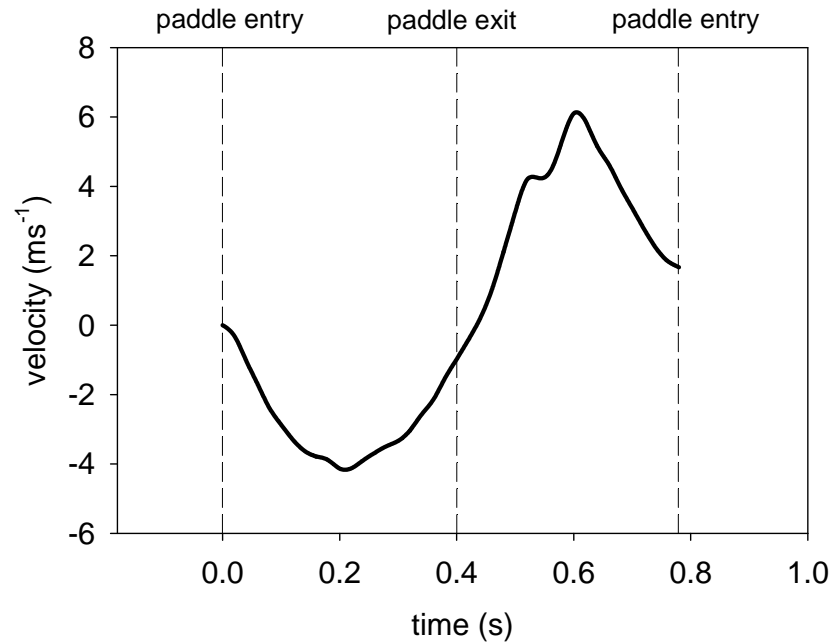


Fig. 4: Paddle horizontal velocity relative to the boat is shown for a complete stroke. Paddle entry and exit points and indicated by vertical dashed lines. Paddle velocity increased (negatively) relative to the boat as the drive phase commenced. A peak velocity was reached approximately half way through the drive phase before reducing towards paddle exit.

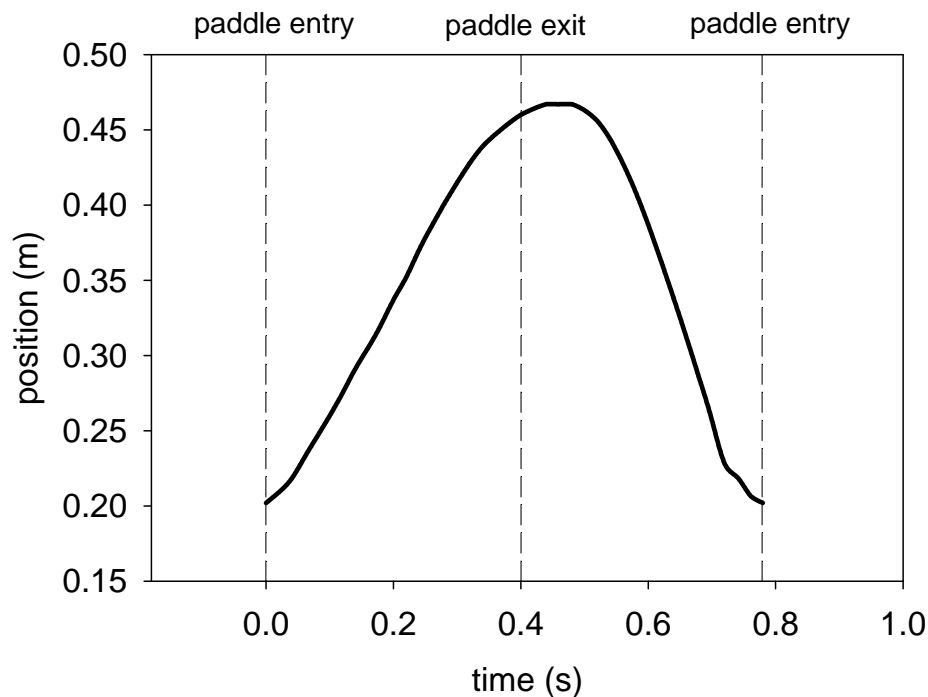


Fig. 5: Padder horizontal centre of mass location is shown for a complete stroke. Paddle entry and exit points and indicated by vertical dashed lines. An amplitude of 0.26m is observed during the stroke.

Paddler centre of mass displacement is shown in Figure 5. During each stroke, the legs remained stationary, with the upper body moving backwards during the drive phase and forwards in the recovery phase. The amplitude of this motion was 0.26 m.

4. Simulations

4.1. Model validation

The input variables used for model validation are shown in Table 1. The model was constructed in Simulink (Mathworks, MA) and solved using a 4th order Runge-Kutta fixed time step solver, with a step size of 0.001 s. The model ran for 20 seconds to ensure a steady state boat velocity had been achieved. Mean steady state boat velocity was subsequently determined for the last complete stroke.

Table 1. Model validation input variables.

Variable	Value
Drive time (s) – τ_1	0.38
Recovery time (s) – τ_2	0.4
Paddler amplitude (m) – a	0.26
Paddler mass (kg) – m_{crew}	52
Boat mass (kg) – m_{boat}	15
Paddle velocity – v_{p-rel}	Measured
Fluid density (kg.m ⁻³) – ρ	999
Paddle area (m ²) – A	0.1233
Peak drag coefficient – C_{D0}	1.7

The model was shown to closely simulate the actual race velocity for the elite paddler confirming the validity of the model. The modelled velocity of 2.89 m s⁻¹ was only 1.3 % faster than the measured mean boat velocity (2.86 m s⁻¹), which was deemed to be within acceptable limits.

4.2. Simulations

The aim of the simulations was to determine whether mean horizontal boat velocity could be changed by introducing an angular offset between the line of the paddle shaft and the line of the blade (Figure 6). A negative offset would result in reduced entry and exit angles for the same angular displacement of the paddle shaft. This offset of the paddle blade could be achieved through modifications to the design of the paddle. Paddle offset was varied in 10 degree increments between -30 degrees and 30 degrees. The paddle trajectory at 0 degrees paddle offset was the same as for the validation simulation.

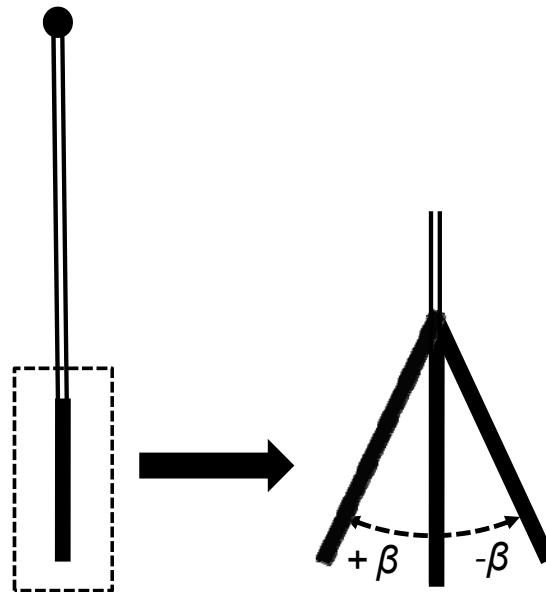


Fig. 6: Side view of the paddle, illustrating the directions of positive and negative angular offset (β) between the paddle blade and shaft. The boat is travelling from left to right.

Figure 7 demonstrates that mean boat velocity was greatest when the paddle offset angle was -20 degrees. The angle of attack at the point of maximum paddle velocity was 34 degrees at an offset of 20 degrees, 14 degrees at an offset of 0 degrees (measured paddle trajectory) and -6 degrees at a -20 degree offset. According to equation (6), peak drag coefficient would be achieved when the direction of fluid flow relative to the paddle blade is perpendicular to the chord line of the blade, or with an angle of attack of zero degrees. The data therefore showed this to occur closest to -20 degrees.

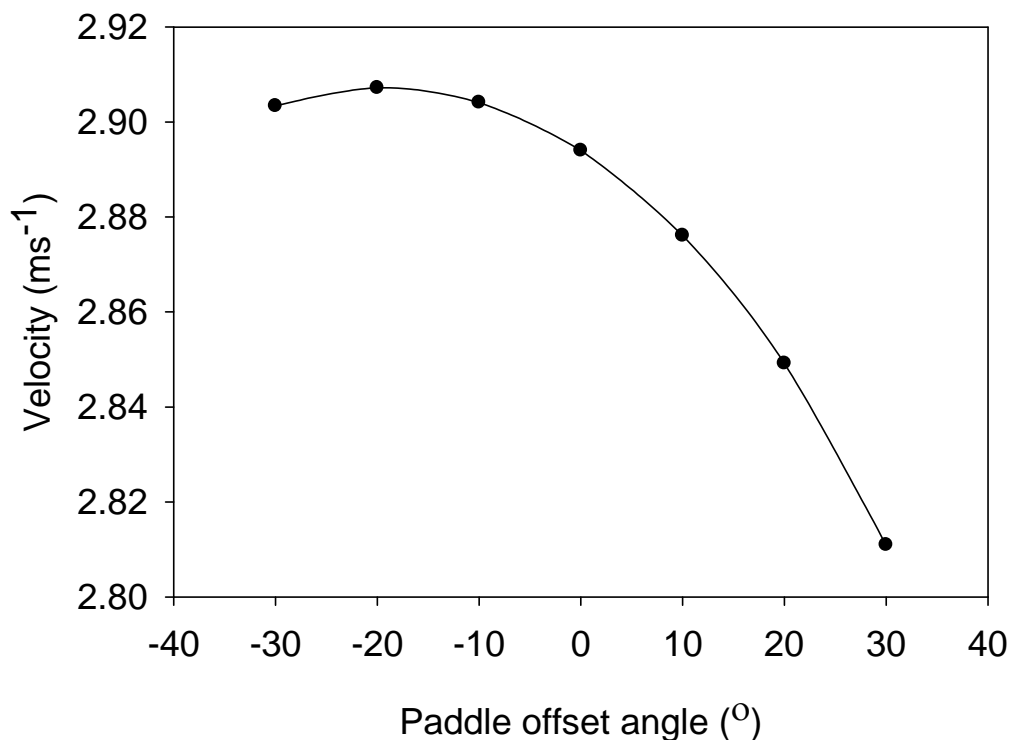


Fig. 7: Mean boat velocity is shown as paddle offset angle is increased from -30 degrees to 30 degrees. Paddle offset angle is the angle made between the line of the paddle shaft and the line of the paddle blade.

5. Conclusions

The aim of this investigation was to develop a mathematical model of the canoe paddling stroke in order to investigate the influence of paddle orientation through the stroke on mean boat velocity. The model, which was based on Newton's second law, was shown to be valid against on-water data for an elite female dragon boat paddler in an O1 outrigger canoe. Due to the availability of appropriate data, it was only possible to validate the model for a single female paddler in an O1 outrigger canoe. Further research should aim to validate the model against data for a range of boat classes and crew sizes.

Paddle offset angle relative to the shaft was adjusted incrementally. The simulations showed that by reducing the angular offset of the paddle blade by -20 degrees, peak mean boat velocity was achieved. The angle of attack when peak paddle velocity occurred was close to 0 degrees for an offset of -20 degrees. This finding suggested, at least for the paddler investigated here, that the fastest boat velocity was achieved by ensuring that the face of the paddle was vertical at the point in the stroke when the paddler had accelerated the paddle to the greatest extent through the water.

These findings suggest that, at least for the paddler investigated here, the orientation of the paddle blade through the stroke should be adjusted to suit the change in paddle velocity generated by the movement of the paddler. In order to more accurately model the stroke, future developments should increase the degrees of freedom of the model to allow for the influences of vertical forces and their effect on the drag experienced by the boat. The effect of yaw, pitch and heaving motions should also be investigated.

6. References

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