# *The Mechanics of Fast-Start Performance of Pike Studied Using a Mechanical Fish*

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# THE MECHANICS OF FAST-START PERFORMANCE OF PIKE STUDIED USING A MECHANICAL FISH

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## ABSTRACT

A northern pike (*Esox lucius*) is capable of achieving a maximum instantaneous acceleration of 25g, far greater than that achieved by any manmade vehicle. In order to understand the physical mechanisms behind achieving such high accelerations, we have built a mechanical fish to emulate the motion of a pike, a fast-start specialist. A live pike bends its body into either a C-shaped or an S-shaped curve and then uncoils it very quickly to send a traveling wave along its body in order to achieve high acceleration. We have designed a mechanical fish whose motion is accurately controlled by servo motors, to emulate the fast-start by bending its body to a curve from its original straight position, and then back to its straight position. Furthermore, this mechanical fish is designed to be adjustable in swimming pattern, tail shape, tail rigidity, and body rigidity, making it possible to study the influence of all of these parameters on the fast-start performance. Peak accelerations of 2.0 m/s$^2$ and peak velocities of 0.09 m/s are measured. Although the maximum accelerations and velocities observed in our mechanical fish are smaller than those of live fish, the form of the measured acceleration signal as function of time is quite similar to that of a live fish. The hydrodynamic efficiencies are observed to be around 12%, and it is shown that the majority of the thrust is produced at the rear part of the mechanical fish – similarly to the live fish.

## INTRODUCTION

The need for locomotion and maneuvering within the unsteady flows of the marine environment has produced, through evolutionary changes, fish that specialize according to a wide range of criteria. An impressive fact is that the accelerations produced by some specialist fishes can far exceed that of manmade vehicles. For example, Harper and Blake [1] reported northern pike peak instantaneous accelerations of 245 m/s$^2$. Fish that use fast-starts for prey capture achieve lower peaks in the accelerations. Each fast-start maneuver can be broken into three distinct stages [2]: (i) the preparatory stage, which is a quick contraction of the fish to either a “C” or an “S” shape; (ii) propulsive stage, which is an aggressive uncoiling of the fish to produce the desired locomotion; and (iii) the final stage, which is a variable phase that may include subsequent propulsive strokes or simply coasting.

There are many studies on fast-start performance of the live fish using various experimental methods [3], both for the escape response and the feeding strike. Harper and Blake [1] reported mean maximum start-up accelerations and velocities of 96 m/s$^2$ and 3.1 m/s for feeding and 150 m/s$^2$ and 3.5 m/s for escape for pike. These values were compiled from 25 pike fast-starts. Of these cases, a single-event maximum acceleration rate of 244.9 ms$^{-2}$ was achieved.

Robotic fish have been previously used to study various mechanisms of fish-like swimming [4]. As an attempt toward understanding the mechanisms of fast-start, we have built a mechanical fish in order to emulate the fast-start performance of fish. The mechanical fish is built based on the most studied fast-start specialist species, the pike. A passively propelled mechanical fish was studied previously [5]. It consisted of a spring steel spine, which stored energy through bending it into a C-shape curve. The fish was covered with a cast urethane body, and was held in a C-shape using strings in a water tank. By releasing the strings, the fish could propel itself forward with a maximum acceleration of around 40 m/s$^2$. Here, we present an actively propelled mechanical fish, which can emulate both the C-type and the S-type fast-start with preparatory as well as propulsive stage. We use this fish in order to study the influence of various variables on the observed acceleration.

## EXPERIMENTAL PROCEDURE

The mechanical fish was built based on the body profile of a pike. It is constructed of a spring steel spine and aluminum ribs, which have the same profile as a live pike. This fish can bend its body to an angle of 90°. Movement is governed by servo motors, which pull on cables attached to certain ribs, bending the fish to a C- or an S-shape. The degree of bending and timing of strokes can be controlled, and the fish can perform either a propulsive stroke only or a full stroke consisting of both the preparatory stage and the propulsive stage.

The interior pockets of the PVC head (Figure 1) were machined in a milling machine, and the outside surface turned on a lathe. The head was designed to have an easy assembly, which would allow for inclusion of an accelerometer as well as various designs for the fish body. The fish rig was mounted on a track on linear ball bearings, as shown in Figure 2. The coefficient of kinetic friction for the track was experimentally determined to be 0.080, by hanging precision weights from a pulley attached to the track. Masses of various components of the fish are given in Table 1. The apparatus allows motion in one direction only.

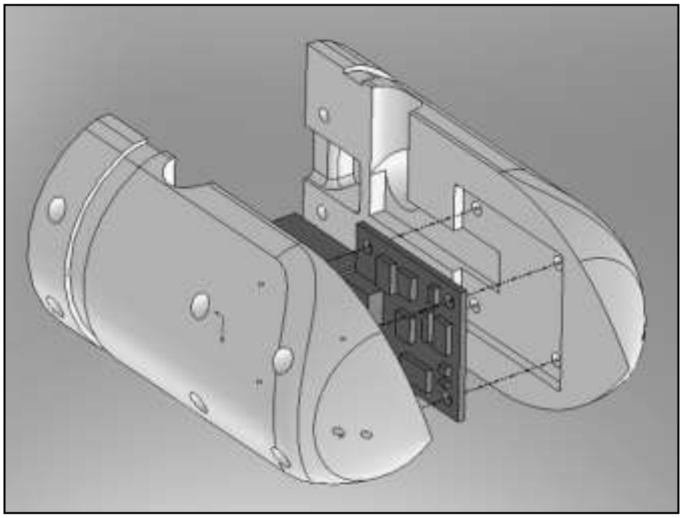

**Figure 1: The PVC head designed for the mechanical fish allows for inserting an accelerometer as well as various designs for the fish body.**

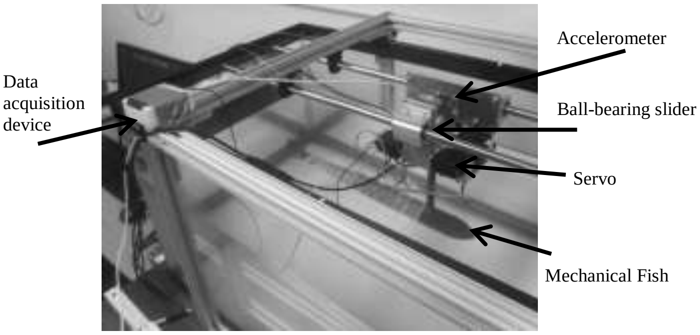

**Figure 2: The experimental setup with key components labeled.**

**Table 1: Masses of Various Components**

| Component | Mass (kg) |
|---|---|
| Platform Total | 1.108 |
| Fish Body | .144 |
| PVC Head | .175 |
| Copper Tube | .106 |
| Added Water Weight | .266 |
| Fish Total | .649 |
| Total Fish Rig | 1.757 |

For each test, the fish was bent to 90°, as shown in Figure 3. The servomotors pull on tension cables running along the body of the fish. When the cable is pulled, it causes the spine to bend to one direction or another. As the servomotor releases the pulled cable, the stiffness of the spring steel forces the spine to unbend. As a result, the spine straightens out and the fish is propelled forward.

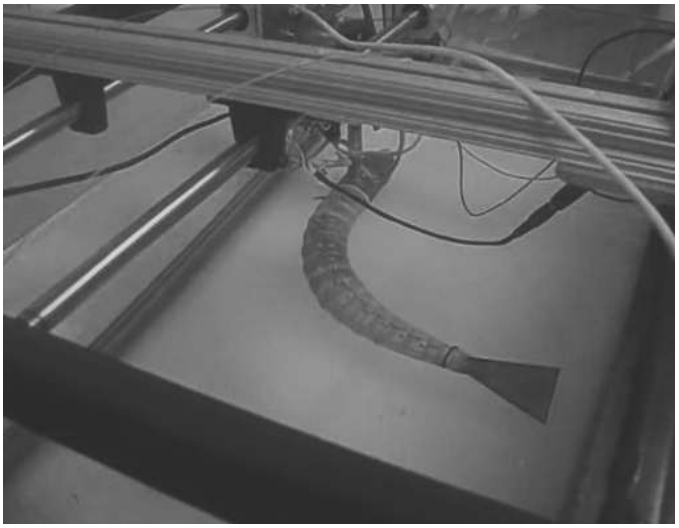

**Figure 3: The fish body bent at 90°. Cables running along the length of the fish's body hold the bent body in the desired shape.**

Acceleration data are collected at a rate of 250 Hz from a Phidget 3/3/3 Spatial IMU. The position of the servomotor is determined from the same potentiometer that the servomotor uses in its internal controller. The voltage across this potentiometer is read using a DATAQ DI-158U data acquisition device and is used to determine servo position and the curvature of the fish's body as a function of time. This operates at a rate of 240 Hz.

Figure 4 shows the acceleration and velocity as measured using the accelerometer. The fish starts from the rest, experiences its maximum acceleration, decelerates, and then stops after moving for around .0187 m.

Figure 5 shows a comparison between the accelerations of the mechanical fish and those of a live fish [6]. When the effect of friction of the track is eliminated, the velocity and acceleration profiles are very similar to those reported by Harper and Blake.

From Harper and Blake [1], the mean distance traveled during a pike's fast-start is around 0.2 m, for an average body length of 0.38 m: about 53% of the body length. In our experiments, and after removing the influence of track friction, the distance of the fast-start was around 0.09 m for a 0.4-meter-long fish, or about 22% of the body length.

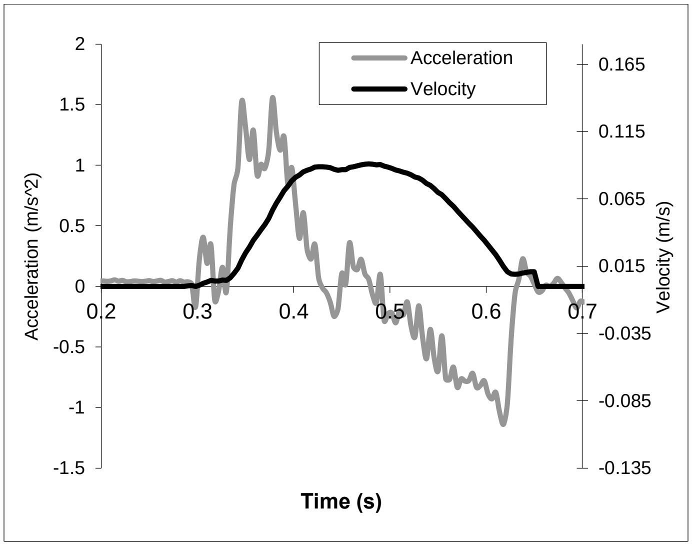

**Figure 4: Acceleration and velocity data as reported by the Phidget 3/3/3 IMU. Note that the track friction generates a constant acceleration of -.785 m/s$^2$.**

## DETERMINATION OF THE BODY CURVATURE

In order to determine the fish's body curvature as a function of the servo potentiometer voltage, a number of photographs were taken of the fish at different degrees of bending. In order to assure that there were no hysteretic effects in the relationship between curvature and voltage, the photos were taken as the voltage increased and again as the voltage decreased. A number of measurements were taken of the fish body in order to supplement the photographic data. These measurements included the distance from the tail mount to the head, the displacement of the tail tip in the forward direction, and the displacement of the tail tip in the lateral direction.

In each photograph taken of the fish, the x- and y-coordinates of the tail tip, tail mount, and ribs were plotted and a spline curve was fit to those points, using the length of the tail and width of the aluminum ribs as reference lengths, as shown in Figure 6. From nine of these images the position of each rib and the tail mount were calculated as a function of servo potentiometer voltage. MATLAB's curve fit toolbox was used to interpolate between the measured points to describe the x- and y-coordinates of each point as a trigonometric function of the potentiometer voltage, and from this the position, velocity and acceleration of each point could be determined relative to the fish's center of mass at any point in time. To find the angle between the spine and the x-axis at each point, the length of the fish's body was interpolated in MATLAB using the Piecewise Cubic Hermite Interpolation Polynomial (pchip) and the derivative at each point was found.

The motion of the center of mass was directly determined from the accelerometer data. The center of mass of the fish was found to be between the first and second vertebrae; displacement in the y-direction of these vertebrae was observed to be negligible. For this reason, the velocity of the center of mass is assumed to be in the same direction as the measured accelerations.

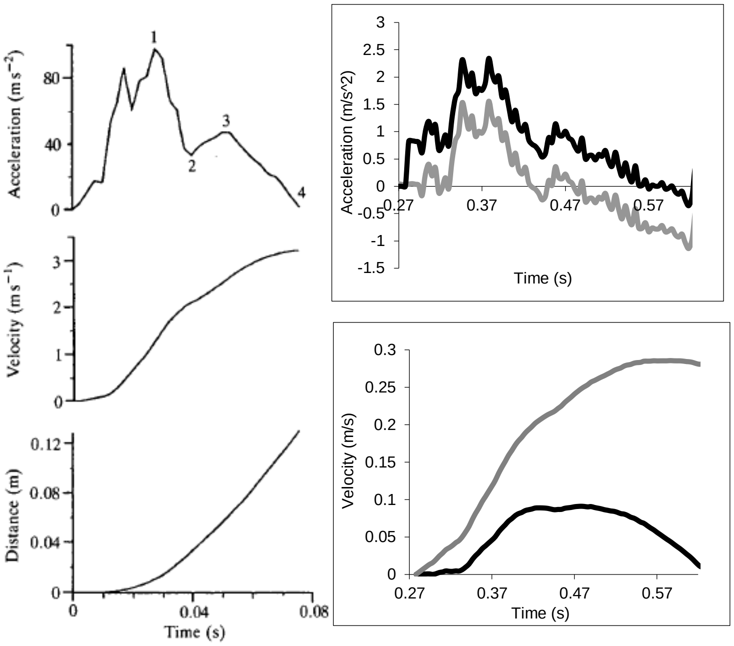

**Figure 5: Live fish recorded measurements [6] (left) as compared with the results of the current tests (right). Note that the effects of the bearing track friction have been removed in the gray lines to better show the measured acceleration of a free swimming fish. The characteristic shape is replicated in the acceleration profiles.**

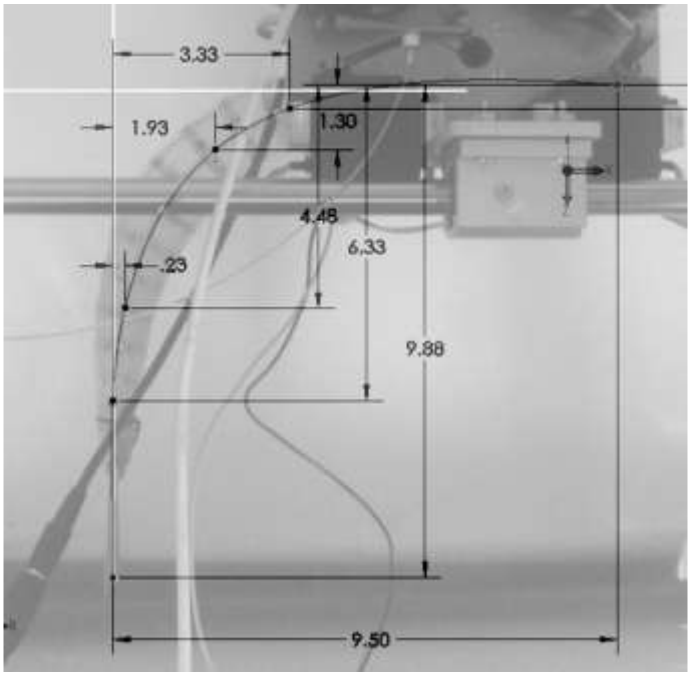

**Figure 6: SolidWorks spline overlaid the image of fish at 356 mV reading on potentiometer voltage. The width of the ribs and length of the tail were used as reference dimensions.**

## APPLICATION OF THE FRITH AND BLAKE MODEL

Frith and Blake [7] determined the hydrodynamic efficiency and total propulsive forces of both C-shape and S-shape fast-start for live fish using a method proposed by Weihs [2]. This method gives the theoretical propulsive force in terms of the motion of segments of the fish's body and their momentum exchange with the surrounding fluid. We apply this method to our mechanical fish in order to analyze the propulsive phase of the fast-start motion.

Weihs model assumes that the forward thrust is generated by the acceleration of the added mass of fluid about each body section. The acceleration of the added mass and the lift forces due to various fins are combined to determine the useful thrust force,

$$F_u = \frac{d}{dt}\int_0^L m_a w\left(\frac{\partial y}{\partial l}\right)dl + \frac{1}{2}\sum_{i=1}^{k}\rho S_i V_i^2 C_{Li}\varphi, \qquad (1)$$

where, $L$ is the length of the fish; $m_a$ is the added mass affected by a longitudinal section of the body of length d$l$; $w$ is the velocity of the segment of the fish of length $dl$ perpendicular to the backbone; $\partial y/\partial l$ *is* the cosine of the angle between the velocity vector of the center of mass of the fish and the orientation of the backbone at each point; $\rho$ is the density of water; $S$ the surface area of each sharp-edged fin; $V$ the velocity of the fin; $\varphi$ the angle of attack; and $C_{Li}$ the coefficient of lift as a function of the angle of attack. The coefficient of lift is determined assuming that the fin is a rigid flat plate. The value of $w$ is determined from the motion capture study as,

$$w = \frac{dy}{dt}\frac{dx}{dl} - \frac{dx}{dt}\frac{dy}{dl}, \qquad (2)$$

where, $dy/dt$ and $dx/dt$ are the velocities of the point considered in the $y$- and $x$-directions, with the $x$-axis defined as the direction of velocity of the fish center of mass (Figure 7).

The value of the added mass is calculated as,

$$m_a = \frac{1}{4}\pi\rho d^2\beta, \qquad (3)$$

where, $d$ is the height of the fish's body and $\beta$ is a shape factor assumed to be approximately equal to 1 for the pike's body shape [8].

While the integral in (1) can be evaluated continuously over the length of the fish, it is found by Frith and Blake [9] that analyzing discrete sections does not significantly reduce the accuracy of the calculations. We divide the fish to eight sections as shown in Figure 8 and Table 2, so that (1) becomes,

$$F_u = \frac{d}{dt}\sum_{n=1}^{7} m_a w_n\left(\frac{\partial y}{\partial l}\right)l_n + \frac{1}{2}\sum_{i=1}^{k}\rho S_i V_i^2 C_{Li}\varphi. \qquad (4)$$

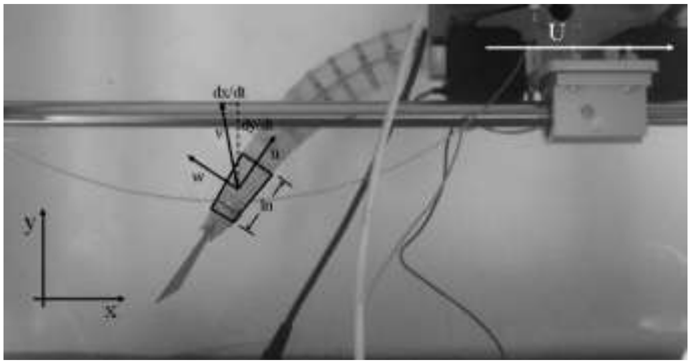

**Figure 7: The variables used in determining the useful thrust force generated by the body motion.**

**Figure 8: The fish is divided to 8 sections. The position of each segment center has been tracked photographically to find the position and orientation of each segment as a function of potentiometer voltage.**

**Table 2: The dimensions of each section of Figure 8**

| Section | Length (m) | Depth (m) | Area ($m^2$) |
|---|---|---|---|
| 1 | .0646 | .0570 | .003682 |
| 2 | .0319 | .0191 | .000607 |
| 3 | .0692 | .0348 | .002407 |
| 4 | .0338 | .0513 | .001736 |
| 5 | .0391 | .0513 | .00206 |
| 6 | .0361 | .0513 | .001852 |
| 7 | .0272 | .0513 | .001396 |
| 8 | .1111 | .0483 | .005363 |
| TOTAL | .4119 |  | .0195 |

The required thrust force for the recorded acceleration, $F_i$, is

$$F_i = (m + m_1)a + 0.08mg, \tag{5}$$

in which, the acceleration, $a$, is the forward acceleration recorded by the accelerometer. The mass, $m$, is the mass of the rig, 1.757 kg, and the mass, $m_1$, is the effective added mass in the forward direction. This is assigned a value of $0.2m$, as was experimentally derived by Webb [10]. Because only 0.649 kg of the total mass is due to the fish itself, the 0.2 is only applied to this portion of the mass, as there is no added mass associated with the servo platform.

## HYDRODYNAMIC EFFICIENCY

Frith and Blake (1995) give the useful power, $P_u$, as

$$P_u = F_u U, \tag{6}$$

where $U$ is the velocity of the center of mass of the fish. The total power exerted by the fish can be calculated as

$$P_t = P_u + \frac{1}{2} m_a w^2 U\big|_{tail\ tip} + \frac{d}{dt}\int_0^L \frac{1}{2} m_a w^2 dl + \frac{d}{dt}\int_0^L \frac{1}{2} m_s \frac{\partial y^2}{\partial t^2} dl. \tag{7}$$

The terms on the right side include the useful power, the power lost to the wake, the power required to accelerate the added mass of water forward, and the power required to accelerate the sections of the fish laterally. The section mass includes both the aluminum members of the fish body and the internally stored water, estimated as a cylinder of water with the length of the body cavity and a diameter equal to the fish's body width. As in Frith and Blake [9], only positive values for the last two terms in (7) are considered, as it is assumed that only passive forces are responsible for negative acceleration of the section mass laterally and of the added mass.

The hydromechanical efficiency found through this method is

$$\eta = \frac{P_u}{P_t}. \tag{8}$$

The calculated useful thrust force as well as the inertial force required to achieve the measured acceleration are plotted in Figure 9. The maximum for the calculated force is 6.4 N, and for the measured required force is 4.1 N. The corresponding peak acceleration and velocity are 1.55 m/s$^2$ and 0.09 m/s, respectively, leading to a hydrodynamic efficiency of around 12%. In calculating this efficiency, the influence of the friction of the track on the efficiency is removed. Because the frictional force generates an acceleration of approximately -0.08g and the recorded accelerations are on the order of 0.15g, this friction, though small, is a significant factor in the performance of the mechanical fish. In order to remove the effect of this friction on the calculated efficiency, we have added an acceleration of 0.08g to the measured acceleration.

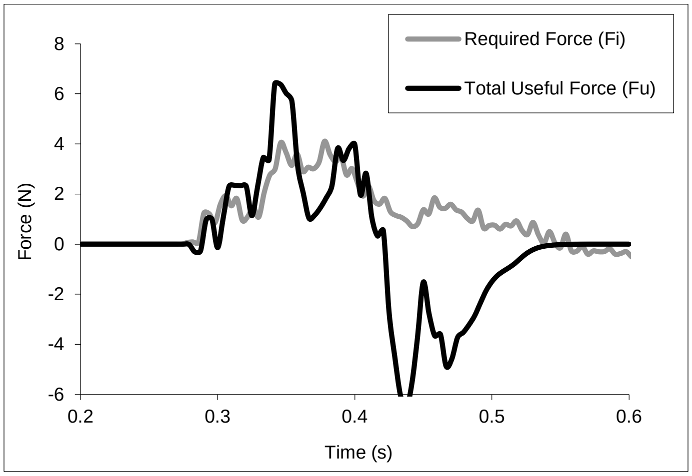

**Figure 9: The total thrust force as predicted by the method used by Frith and Blake [9] and the force required to achieve the motion measured using the accelerometer, after removing the influence of the friction of the track.**

There is qualitative agreement between the predicted force patterns from our mechanical fish and those from Frith and Blake's experiments [6]. Figure 10 shows a side-by-side comparison of the previous work with live fish and our results. Only the propulsive stage was emulated in our tests, so the area of consideration is between the arrows marking S1 and S2 in the figure, which are the end of the first stage and the end of the second stage. The key features—two large positive acceleration peaks followed by a negative acceleration peak of similar magnitude—are observed.

A key difference is that of the timing of the stages. In Frith and Blake's work, the length of the second stage, the propulsive stage, of the fast-start motion was less than 0.1 s; in our experiments, it was just over 0.2 s. The speed of the motion is a critical factor in achieving the large accelerations observed in live fish.

The section contribution to thrust forces followed a similar pattern to those for a live fish. In our experiments, the tail section was responsible for around 78% of thrust generation. This is very similar to the results of Frith and Blake [7] where it was found that the caudal fin is responsible for approximately 77% of the positive thrust during the propulsive stage. Thrust force was dominated by the rear four sections—the front four had negligible contributions.

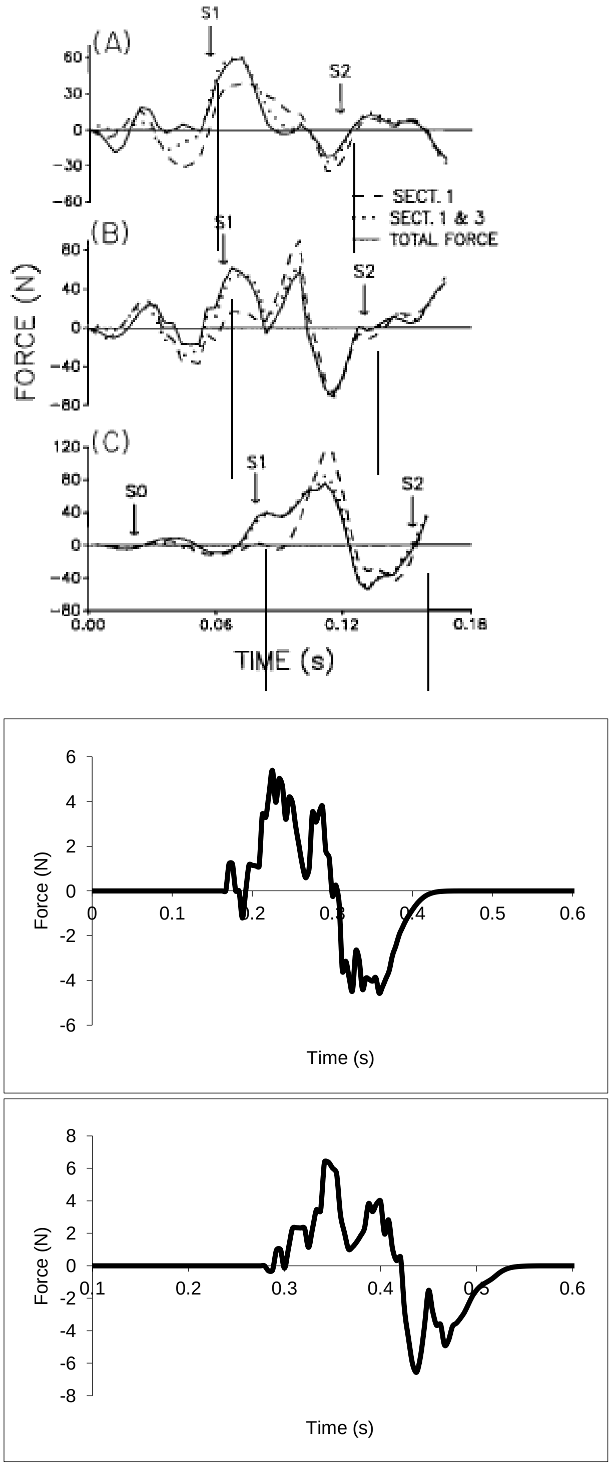

**Figure 10: A side-by-side comparison of three trials by Frith and Blake [7] (up) and the results of two trials of our mechanical fish with only the propulsive stage (down). The characteristic two peaks followed by a negative peak can be seen.**

## CONCLUSIONS

In order to study various fast-start mechanisms, we have built a mechanical fish, which emulates the fast-start of a pike by bending its body from straight to a C- or an S-shape, and then uncoiling it to propel forward. This mechanical fish achieves a peak acceleration of around 2.0 m/s$^2$ and a maximum velocity of 0.09 m/s. This is considerably smaller than the acceleration and velocity of a live fish, which can be on average up to 151 m/s$^2$ and 3.4 m/s [9]. However, the patterns in the measured acceleration, as well as in the calculated thrust force of our mechanical fish are very similar to those of a live fish. This suggests that we can use this mechanical fish to explore experimentally various hypotheses on the fast-start mechanisms (e.g., those regarding the influence of the shed vortices on the resulting fast-start) by conducting tests in a controlled environment. The observed hydrodynamic efficiency of the fast-start is around 12% – comparable with those calculated for a live fish: 16-39%. Following the method of Frith and Blake [9], we show that around 78% of the forward thrust is generated at the rear part of the fish – in close agreement with the value calculated for live fish: 77%. A previous mechanical fish [5] can achieve a larger maximum acceleration (around 40 m/s$^2$), performing only the propulsive stage. The current mechanical fish, however, has the capability of including the first stage (preparatory stage) to the fast-start, and also can be used to test the influence of various system parameters (e.g., tail surface area, body stiffness, radius of curvature, …) on the resulting efficiency.

The relatively low values for the maximum acceleration and the final velocity owe themselves to the low power available to the mechanical fish. Live pike have available muscle outputs of 195.7 W/kg of muscle mass [9] and 100 W/kg of total weight [10], with the theoretical limit for vertebrates being 500 W/kg. Our mechanical fish possesses only the 0.92 J of stored energy in a very slender beam, despite a mass of 0.65 kg. If all of the energy were expended in 0.2 seconds, the power output would only be 4.6 W, or 7% of what an actual fish of the same size would be capable to generate.

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