Abstract: In this research, we present an *in silico* approach for designing the caudal fin of a carangiform robotic fish. Simulations are performed in a dynamics environment, which includes the hydrodynamic forces acting on a flexible caudal fin. Two approaches are employed to adjust caudal fin parameters with the goal of maximizing average velocity: a hill-climber and a genetic algorithm. Simulated caudal fins are compared to 3D printed fins that are validated in an aquatic test environment.

Dynamic Model
A carangiform fish generates thrust primarily with a caudal fin. The hydrodynamics forces involved with caudal fin motion are shown in the figure below.

![Dynamic Model Diagram](image)

In this model, a caudal fin is divided into equal sized segments and the hydrodynamic forces are evaluated independently for each segment. The fin segments are connected to each other by torsion springs; the torsion spring coefficients are related to material flexibility (Young’s Modulus).

Simulation Environment
Given the unique challenges associated with modeling the fluid dynamics of an aquatic environment, the Open Dynamics Engine was used in conjunction with the dynamic model to approximate the hydrodynamic forces acting on a caudal fin. The figure below shows the approximation of the robotic device.

![Simulation Environment](image)

Hill Climber Results
The Figure below shows the performance (average velocity) of a robotic fish when the caudal fin stiffness is manipulated. The key aspect of the figure is that intermediate values of the Young’s modulus produce the fastest robot. The model, however, assumes that the body remains anchored, and that the caudal fin segments are without mass. Both of these assumptions will cause a disparity between simulation and reality.

![Hill Climber Results](image)

Physical Results
Six fins were tested on a robotic fish prototype (right side of figure below); the materials range from extremely flexible to nearly inflexible. The data, left side of the figure below, shows the same predicted relationship between flexibility and average velocity in which an intermediate flexibility produces the highest average velocity.

![Physical Results](image)

Genetic Algorithm Results
In our final set of experiments, fin shapes were evolved along with flexibility. The figure below shows the fitness landscape for fins with different parameters. As the length of the fin increases, the Young’s Modulus increases as well to maintain similar stiffness fins for different lengths.

![Genetic Algorithm Results](image)

These results demonstrate the effectiveness of an evolutionary based approach given the non-linear dynamics of an aquatic environment.

Acknowledgments: The authors gratefully acknowledge support for this research provided by the National Science Foundation and the BEACON Center for the Study of Evolution in Action.