# MODELING AND SIMULATIONS OF COMPLEX DYNAMIC MUSCULOSKELETAL ARCHITECTURES

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## EXECUTIVE SUMMARY

Is the familiar goldfish hiding a technological treasure? Seemingly simple, its wandering around a bowl involves complex interactions between its senses, body, and the surrounding water. More generally, during millions of years of evolution, animals have refined sophisticated design solutions to master their complex interplay with the environment. How can we understand the biophysical mechanisms at play and translate them into rational design principles?

To inquire into the fundamental mechanisms underlying continuous, distributed biological actuation and control, we have developed a novel mathematical formulation based on assemblies of Cosserat rods, rods with deformable cross-sections, for the modeling of complex soft musculoskeletal architectures interacting with surrounding environments. These techniques are embedded in an automated inverse design cycle based on evolutionary optimization. This allows us to set a desired trait (speed, dexterity, energy efficiency) and to identify optimal designs and muscle actuation sequences in response to sensory cues.

## RESEARCH CHALLENGE

All animals are constantly confronted with the physics of the surrounding media. Whether natural creatures can take advantage of physics to push their performance limits depends on their biological strategies, from materials, morphologies, and gaits to collective behaviors. Their struggle for survival has produced a rich array of solutions that often outperform engineering designs and work in ways we still do not fully understand. These solutions bear a great potential for technological innovation, with applications ranging from robotics to energy harvesting devices.

In this context, bioinspired approaches rely on mimicking existing natural solutions to enhance the performance of current engineering designs. Nevertheless, one may question to what extent engineers should follow biomimicry. Indeed, natural creatures have not evolved to optimize engineering objectives, and we have limited information to determine whether a particular solution optimally serves a given function. Moreover, today's materials and components pose constraints and enable opportunities that may differ from their biological counterparts. Hence, we suggest that manmade solutions obtained through inverse design based on an automated optimization process may outperform pure biomimicry.

## METHODS & CODES

The characterization of biopropulsion from an optimality standpoint demands accurate, robust, fast, and flexible numerics for flow–structure interaction problems. We have been developing and implementing novel schemes for the direct numerical simulation of individual and multiple swimming bodies. Our algorithms rely on remeshed vortex methods enhanced with projection approaches to capture the effects of the fluid on the body and, with penalization techniques, to capture the effects of the body on the fluid [1,2]. This methodology is coupled with a musculoskeletal solver developed to capture the compliant dynamics of musculoskeletal systems made of bones, tendons, and muscles [3].

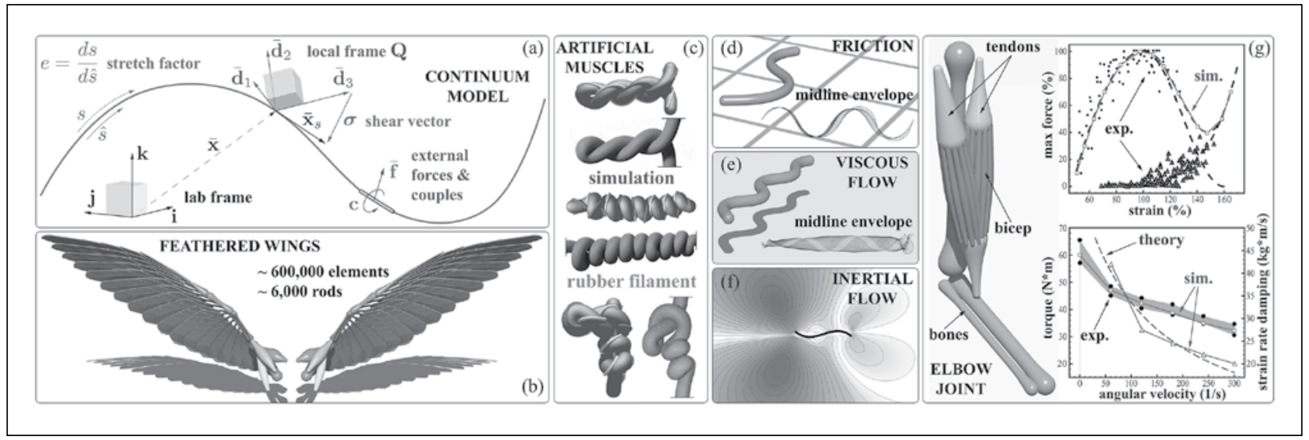

Figure 1: *Elastica* capabilities. (a) Continuum model. Applications to (b) feathered wings, (c) topology and mechanics in artificial muscles, (d) slithering snake, (e) swimming spermatozoa, (f) flexible foil in inertial flow, (g) elbow joint.

## RESULTS & IMPACT

We have developed *Elastica* [3], a software able to capture the dynamic response of complex musculoskeletal structures. We validated our solver on a number of benchmark problems with known analytic solutions and against experimental investigations involving (self-)contact, anisotropic surface friction, and highly viscous and inertial fluids. We also verified the solver experimentally in the context of artificial muscles, linking topological changes to mechanical work, and extended it to simulate arbitrary complex musculoskeletal layouts from wings to human elbow joints (Fig. 1).

We then employed *Elastica* to computationally design, simulate, and optimize for the first time the structure of a biohybrid walking bot (Fig. 2). In collaboration with experimentalists at the Micro and Nanotechnology Laboratory, our design was fabricated and tested, confirming our predictive capacity and leading to the largest, fastest locomotive bot to date [4].

## WHY BLUE WATERS

Blue Waters' sheer size and cutting-edge technology enable optimization processes that entail thousands of simulations. This allows the design of unprecedented biological architectures, bringing novel high-impact applications within reach, from soft robotics and biomedicine to precision manipulation and fabrication.

## PUBLICATIONS & DATA SETS

Gazzola, M., L. Dudte, A. McCormick, and L. Mahadevan. Forward and inverse problems in the mechanics of soft filaments. Accepted in *Royal Society Open Source*, (2018), arXiv:1607.00430v2.

Pagan–Diaz, G.J., et al., Simulation and fabrication of stronger, larger and faster walking biohybrid machines. *Advanced Functional Materials*, (2018), DOI:10.1002/adfm.201801145.

Figure 2: Top view of three thumb-sized biobots in a culture dish. Modeling and simulations were employed to design and optimize function and performance. These biohybrid machines walk on the dish surface at about one millimeter per second.