# Body/Brain Co-Evolution in Soft Robots

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## Extended Abstract

Autonomous Robots have achieved considerable results in a wide variety of domains, from the depths of the ocean to the surface of Mars, and yet many vital locations, particularly collapsed buildings and mines, remain largely inaccessible. In light of recent natural disasters in Haiti and Chile, there is a compelling need for more versatile and robust search and rescue robots. Imagine, for instance, a machine that can squeeze through holes, climb up walls, and flow around obstacles. Though it may sound like the domain of science fiction, modern advances in materials such as silk polymers (Huang et al., 2007) and nanocomposites (Capadona et al., 2008) such a "soft robot" is becoming an increasing possibility.

By soft, we mean an ability to significantly deform and alter shape at a much higher level of detail than discrete "modular" snake-like robots (such as Yim's Polybot Yim et al. (2000) and Rus's Molecubes (Kotay et al., 1998)). In fact the degree of deformability demanded of truly soft robots requires that they contain no rigid parts at all. Unfortunately, the incredible flexibility and deformability demanded of soft robotics carry with them considerable complexity.

There are two significant and coupled challenges to the creation of soft robots: no one knows how to design soft robots, and no one knows how to control them. These challenges arise from the complex dynamics intrinsic softness. Soft and deformable bodies can possess near-infinite degrees of freedom, and elastic pre-stresses mean that any local perturbation causes a redistribution of forces throughout the structure. As a consequence, there are no established principles or purely analytical approaches to the problem of soft mechanical design and control To make matters worse, the biomechanics of soft animals are too complex and too inscrutable to provide much useful insight.

Consider what might seem like a relatively simple completely soft animal: *Manduca sexta*, the tobacco hornworm. The caterpillar achieves remarkable control and flexibility despite the fact that each of its segments contains relatively few motoneurons (one, or maximally two per muscle, with approximately 70 muscles per segment), and no inhibitory motor units (Levine and Truman, 1985). It is conjectured that the complex and coupled dynamics caused by the interaction of hydrostatics, an elastic body wall, and nonlinear muscular behavior, are all harnessed and exploited by the organism (Trimmer, 2007).

This relationship between morphology and control in biology is a richly studied and fascinating topic. Recent research on the tendinous network of the human hand indicate that the system performs "anatomical computation". It is conjectured that "outsourcing" the computation into the mechanics of the structure allows related neural pathways to devote their resources to higher level tasks (Valero-Cuevas et al., 2007). Similar phenomena have been shown in the physiology of wallabies (Biewener et al., 2004) and cockroaches (Ahn and R.J.Full, 2002). Pfeifer and Paul (2006) coined the term "morphological computation" to describe this class of effect. Blickhan (2007) has similarly used the phrase "intelligence by mechanics".

Biological morphological computation has served as inspiration for robotic control in several recent works. Iida and Pfeifer (2006) explored how the body dynamics of a quadraped robot can be exploited for sensing. Watanabe *et al* (2003) demonstrated how inducing long distance mechanical coupling in a snake robot improves its ability to learning a crawling motion. All of these systems, however, involved relatively rigid robotic platforms, and relatively well understood mechanics and dynamics.

An outstanding challenge, therefore, lies in discovering how to inject the properties of this "morphological computation" into soft robots. Classically, engineers design complex robotic systems and only later try to find a controller capable of operating it. However, this approach has difficulty scaling – it is entirely possible to design a robot too complex to reasonably control. Of course, biology doesn't first "discover" an animal's body, and only later its brain, rather, much like the proverbial chicken and egg, both evolve in tandem. Inspired by those biological processes, modern approaches to the Evolutionary Design of robots by co-evolving morphology and control (Pollack et al., 1999; Sims, 1994).

In this work we show how the chicken-and-egg problem of soft robotic design and control can be addressed via body/brain co-evolution. A co-evolutionary algorithm operating within the PhysX physics simulator simultaneously searches for soft robot muscle attachment points (morphology) along with for firing patterns for those muscles(gaits) capable of making those bodies move. More specifically, two parallel populations are evolved: fitness of the population of gaits relies upon the current best evolved body plan, and fitness of the population of body plans relies upon the best evolved gait. By evolving these two properties contingently and in lock-step, our algorithm is able to produce effective, and sometimes surprising, soft bodied gaits. One particularly interesting outcome is the emergence of antagonistically-placed muscle groups as an effective feature, whereas intuition would suggest that body wall elasticity obviates such a need. This "discovered" design feature was then fed back into physical prototypes of a soft robot, leading to improved real-world performance.

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