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## 2.6 Concluding Remarks / 40

### References / 41

## 2.1 Biological Inspiration

Human-made mobility platforms excel on paved roads, but off road they often get stuck in the dirt. It has been argued that we need legged mobility platforms to negotiate irregular terrain. The development of such legged mobility platforms has been in process for some decades, and only recently have these efforts led to platforms with acceptable performance [Buehler et al., 2000; Cham et al., 2001]. There appears to be something inherently difficult about legged locomotion, even though biological creatures make it seem so simple. Finding out how this feat is accomplished could greatly benefit the development of legged mobility platforms.

Biomechanics is the discipline intended to reveal the mechanisms of animal locomotion. Although we have gained much insight into how animals move and how performance is determined by muscle properties and central nervous control, very little of this knowledge has been transferred to legged mobility platforms with extraordinary performance. This may be in part because biomechanics studies how nature does what engineers have shown to be possible [Vogel, 2001]. In recent years it has become clear that if we want a human-made mobility platforms to move like its biological counterpart, we need to integrate a wide range of disciplines (biomechanics, neurosciences, computational modeling, “biomaterials,” and design) into a new discipline called biomimetics. This discipline involves abstracting principles from nature and offering *biological inspiration* to engineers.

To make such an abstraction is no simple task, and there are several important considerations to be made [Full and Meijer, 2001]. First, nature’s designs are the result of evolution. Animals carry their evolutionary history with them. Many of their constituting parts were first evolved in different environments and have been put to use for new tasks through the course of evolution. Many parts have multiple functions, not excelling at any particular task but performing sufficiently nevertheless. Blind copying of nature is likely to fail because evolution works on a “just good enough” principle [Vogel, 1998]. Nature is a source of inspiration for what is possible and gives design ideas that may have escaped our considerations.

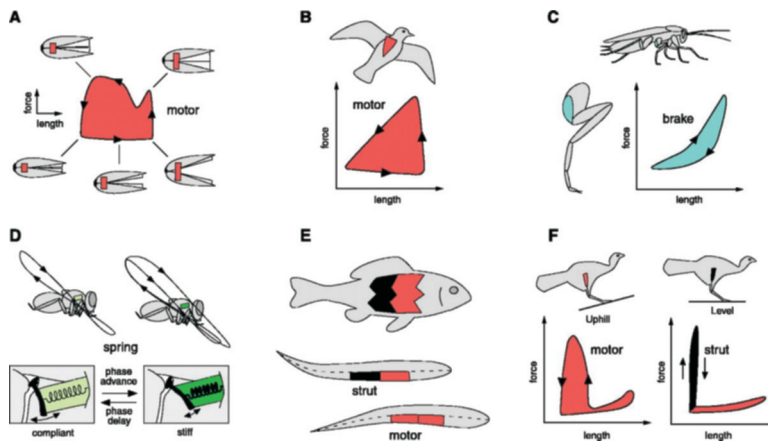
Second, one has to deal with the complexity of biological systems. Animal behavior stems from a complex interaction with the environment. Most legged animals have multiple appendages, actuators and sensors, which are all used when performing relatively simple tasks like walking or running. Looking for synergies can reduce the apparent redundancy and reveal the general principles that underlie the examined behavior. For instance, the walking of legged animals can be compared to the motion of an inverted pendulum, exchanging gravitational potential energy for kinetic energy and vice versa, while the running of legged animals resembles the bouncing of a ball regardless of how many legs they have [Full and Koditschek, 1999].

Third, the chance of successfully capturing biological motion in a mechanical design increases if materials are used that have similar characteristics as biological materials. Human technologies are in general large, flat with right angles, stiff, rolling devices with very few sensors and actuators. Nature's technology, on the other hand, is compact with compliant curved bends and twists that uses appendages with multiple sensors and actuators [Vogel, 1998]. With the emergence of new soft materials and actuators [Bar-Cohen, 2001(a)] we may be able to start using nature's design ideas to our benefit.

## 2.2 Muscle: A Prime Mover

Legged locomotion is accomplished by an integrated, tuned system that includes multiple muscles, joints and sensors, a transport system for fuel delivery, and a complex control system, all functioning through skeletal scaffolding [Full and Meijer, 2001]. It is impossible to address all these aspects within this chapter; instead the focus will be on the unique contributions of human muscles. With the aforementioned principles in mind, natural muscles will be examined to discover how they enable the spectacular performances of various animals. Cheetahs can run, dolphins can swim, and flies can fly like no artificial technology can. An understanding of what muscle uniquely contributes to locomotion must be developed if artificial muscle is to be designed. Natural muscle is a formidable actuator that performs multiple functions, meeting the requirements for successful locomotion such as stability, energy efficiency, and goal directedness. Biologists have elucidated the diversity in muscle function through experiments in which function has been determined by replaying *in vivo* muscle activity and strain patterns in isolated muscle [Josephson, 1985; Marsh and Olson, 1994; Full et al., 1998]. More recently, new technologies have enabled direct measurements of function [Dickinson et al., 2000]. These experiments have yielded insight in the versatile way muscle operates. It has been discovered that muscles act as motors, brakes, springs, and struts (Fig. 2.1) and new functions, such as damping, are still added to that list [Wilson et al., 2001].

The multifunctionality of natural muscle distinguishes it from any human-made actuator and may hold the key to the success of legged locomotion in animals. The development of artificial muscles is a worthy endeavor, which may open up the way for legged mobility platforms. Our knowledge of biological muscle should assist us in constructing an actuator with performance capacities thus far only observed in animals. Multifunctionality in muscle is achieved in part by variation in muscle tissue characteristics; however, much of the functional tuning comes from the way muscles are put together. Structure determines function; in fact, in many biological tissues it is hard to distinguish between material and structure [Gordon, 1976]. Natural muscles come in a variety of shapes and sizes. By studying how muscle tissue characteristics and muscle structures are tuned to facilitate the magnificent performance of animals, we can gain valuable insight for the development of artificial muscles. The transfer of knowledge from biology to human-made actuators becomes more feasible now that new



**Figure 2.1** Examples of the various functions that muscles fulfill. Muscles can act as motors, brakes, springs, and struts. Muscles that generate positive power (motors) during locomotion, and the area within associated work loops, are indicated in red; muscles that absorb power during locomotion (brakes), and the area within associated work loops, are indicated in blue; muscles that act as springs of variable stiffness are indicated in green; muscles that act to transmit the forces (struts) are shown in black. (a) Scallop muscle during swimming [Marsh and Olson, 1994], (b) the pectoralis muscle of birds during flight [Biewener et al., 1998(b)], (c) leg muscles of running cockroaches [Full et al., 1998], (d) intrinsic wing muscle of flies involved in steering [Tu and Dickinson, 1996], (e) alternating roles of fish muscles during swimming [Altringham et al., 1993], and (f) dual role of gastrocnemius muscle in running turkeys [Roberts et al., 1997]. (Image reprinted with permission from Dickinson, M. H., C. T. Farley, R. J. Full, M. A. R. Koehl, R. Kram, and S. Lehman, “How animals move: an integrated view,” *Science*, 288, pp. 100–106. American Association for the Advance of Science © 2000.)

materials like electroactive polymers (EAPs) have become available [Bar-Cohen 2001(a)]. The remainder of this chapter will serve as a guide through some of the classic metrics of muscle function that can allow comparisons, review the functional aspects of EAP materials, and present some of nature’s muscle designs that may be used as inspiration for the development of true artificial muscles.

### 2.3 Muscle Metrics

Muscles, in general, are considered force generators, and most of the experiments reported in the biological literature focus on the factors that determine muscle-force production, i.e., neural activation, length, and contraction velocity. Several excellent reviews on the diverse aspects of muscle force production are available [Full, 1997; Josephson, 1993; Rome, 1997]. In previous publications [Full and Meijer, 2000 and 2001; Meijer et al., 1999 and 2001] we have summarized the range of performance metrics of muscle and discussed their relevance for the

development of artificial muscles. In this chapter, we will briefly review the most important metrics, but the emphasis of the chapter will be on the structural solutions that nature has found to optimize muscle performance for a variety of tasks.

### **2.3.1 Force, strain, and speed**

#### *2.3.1.1 Maximum force production*

The maximum force that an active muscle can generate is always measured at a fixed length at which the muscle is not allowed to shorten. Under these *isometric* conditions, the force generated by a muscle is solely dependent on neural activation. The force response to a single neural stimulus is called a twitch. Consecutive stimuli in the form of a train of neural spikes lead to a summation of force. Maximum isometric force is attained at high stimulation frequencies (typically between 30–200 Hz) when the muscle is in tetanus. Maximum force increases with the cross-sectional area of the muscle, and the values found for maximum isometric stress range from 0.7–80 Ncm<sup>-2</sup> [Josephson, 1993; Full, 1997].

#### *2.3.1.2 Length dependence of force production*

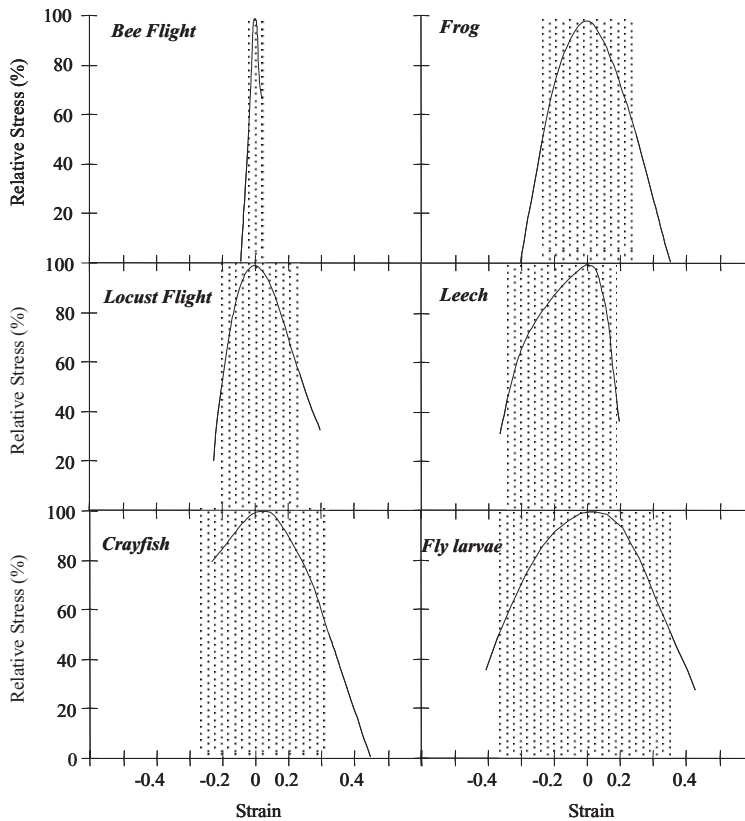
Muscle-force production is length dependent due to the filamentous nature of muscle contraction [Gordon et al., 1966]. In cardiac muscle this length dependency is known as Starling's Law. In skeletal muscle, the length at which a muscle attains maximum force is called the optimum length. Below and beyond this length active muscle force declines again. The length-force curve of muscle determines the range over which active force can be generated. The width of the active length-force curve varies greatly between muscles (Fig. 2.2). The largest difference is observed when flight muscle is compared with the body-wall muscle of insect larvae [Full, 1997]. Flight muscle, which is involved in high-frequency vibrations, can only generate maximum force over a very narrow range of strain (2–4%). By contrast, soft-bodied animals, like larvae, that undergo considerable shape changes have muscles that operate over a large range of length changes (200%).

#### *2.3.1.3 Kinetics of force production*

The rate at which force can be generated and relaxed is a very important determinant for muscle performance during rhythmic activities. Contraction times to peak force range from 0.004–0.79 sec, whereas time to 50% relaxation ranges from 0.009 to as long as 1.1 sec. The fastest muscles are the ones involved in insect flight and sound production [Rome, 1998].

#### *2.3.1.4 Velocity dependence of force production*

Muscle force declines with increasing shortening speed; or in other words, muscles can move light loads faster than heavy ones. The relationship between force production and contraction speed shows the characteristic rectangular hyperbolic



**Figure 2.2** Active strain-stress curves for bee flight, locust flight, crayfish, frog, leech, and fly larvae muscle. [Full, 1997]. Stress is normalized to the peak isometric tension. Strain is normalized as a fraction of the length that gives peak isometric stress. Shaded areas represent strains that correspond to stresses above 50% maximum isometric stress.

shape, which is determined by the maximum isometric force, the maximum shortening velocity, and two shape constants (Hill, 1938). The maximum shortening velocity ranges from 0.3 to 17 lengths/sec (Full, 1997; Josephson, 1993). Less data are available on lengthening muscle, but when muscle is stretched muscle force exceeds the maximum isometric force by nearly twofold.

### 2.3.2 Capacity to do work

A muscle's capacity to do work or generate power can be estimated from the above-mentioned metrics. The product of maximum force and length change can yield an estimate of maximum work output. This method is generally used to compare different actuator technologies (Wax and Sands, 1999). Power output can be estimated from the force-velocity curve, and for a single contraction