

Chapter 2

Biological Inspiration for Musclelike Actuators of Robots

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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

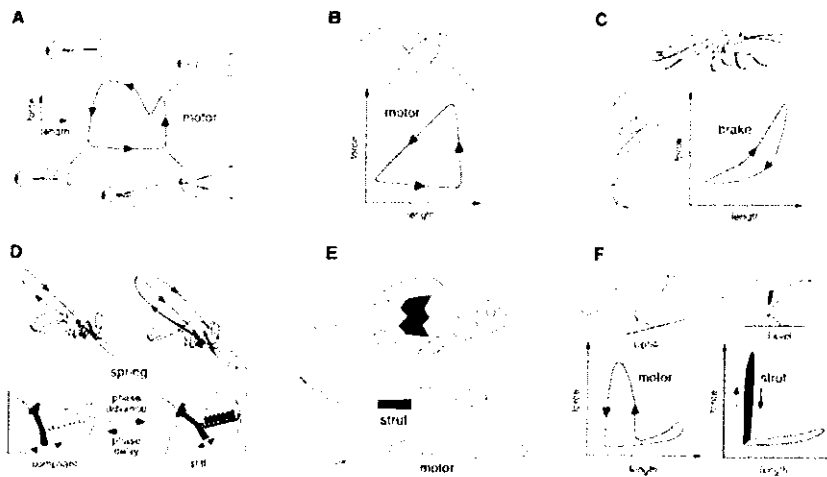


Figure 2.1 Examples of the various functions that muscles fulfill. Muscles can act as motors, brakes, springs, and struts. Muscles that generate positive power (motors) during locomotion, and the area within associated work loops, are indicated in red; muscles that absorb power during locomotion (brakes), 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⁻² [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

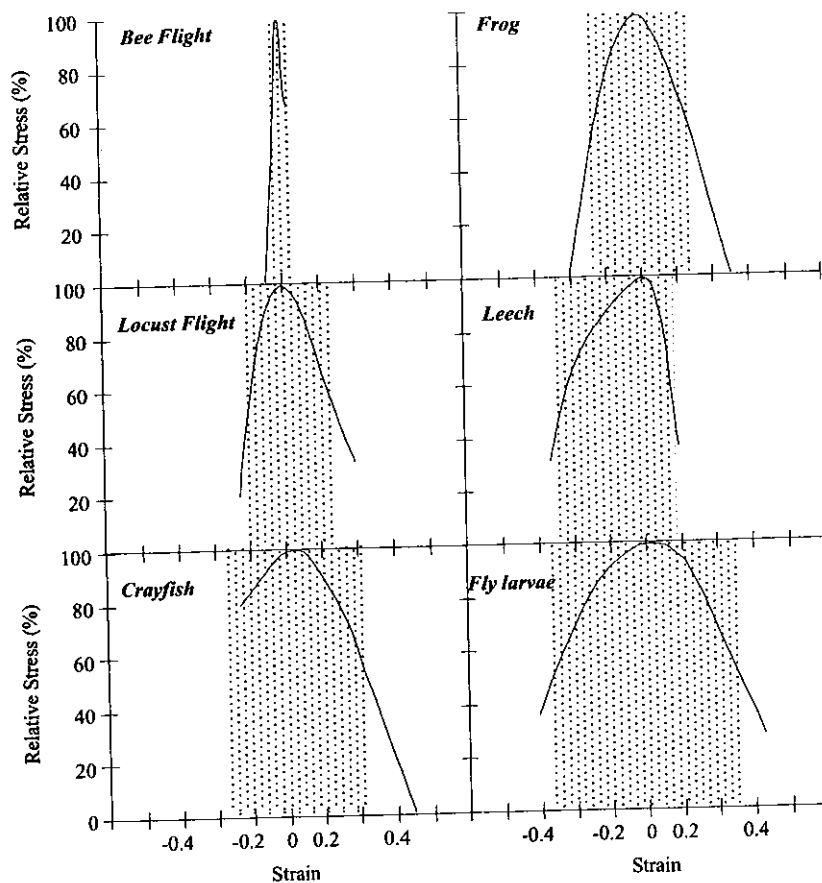


Figure 2.2 Active strain-stress curves for bee flight, locust flight, crayfish, frog, leech, and fly larvae muscle. [Full, 1997]. Stress is normalized to the peak isometric tension. Strain is normalized as a fraction of the length that gives peak isometric stress. Shaded areas represent strains that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

maximum power output generally occurs at one third of the maximum shortening velocity of muscle. These methods give work and power output values for single contractions, but they tend to overestimate the actual work and power output of animals operating in a rhythmic fashion by nearly twofold (Josephson, 1989).

2.3.3 Realized performance: the work-loop technique

The aforementioned metrics are generally determined under static conditions and for single contractions. Animals, however, are involved in rhythmic activities such as walking, running, swimming, flying, chewing, and communicating. Muscle performance under these circumstances is determined by cycle frequency, level and pattern of neural stimulation, phase of neural stimulation as well as strain pattern and magnitude. The influence of each of these parameters on muscle performance can be studied using the *work-loop technique* (Josephson, 1985). With this method, muscle is subjected to cyclical length changes while being stimulated rhythmically. Recent experiments in which this method was used to impose the actual strain patterns and stimulation patterns on muscle have revealed the very diverse roles muscles have during locomotion. Not only do static metrics overestimate work production and power output, in many instances muscle does not even produce any power. Muscles can function as springs, dampers, and struts as well (Fig. 2.1). Thus, in order to develop an artificial muscle, focus should not solely be on the static metrics. Instead, the materials under rhythmic conditions should be compared as well.

2.4 Electroactive Polymers as Artificial Muscles

There are a few examples of legged robots that are successful in achieving biologically like performance [Buehler et al., 2000; Cham et al., 2001], but in general there is still a large gap between the performance of robots and nature's creatures. The required technology is multidisciplinary and has many aspects, including the need for actuators that emulate muscles. The potential for such actuators is becoming increasingly feasible with the emergence of effective *electroactive polymers* (EAP) [Bar-Cohen, 2001(a)]. Polymers have many attractive characteristics, including their light weight, fracture tolerance, and pliability. Further, they can be configured into almost any conceivable shape, and their properties can be tailored to suit a broad range of requirements. During the last 10 years, new polymers have emerged that respond to electrical stimulation with a significant shape or size change, and this progress has added an important capability to these materials. These materials have functional similarities to biological muscles, including resilience, damage tolerance, and large actuation strains (stretching, contracting, or bending). EAP-based actuators may be used to eliminate the need for gears, bearings, and other components that complicate the construction of robots and are expensive, heavy and fail prematurely. Visco-elastic EAP materials can potentially provide more lifelike aesthetics, vibration and shock dampening, and more flexible actuator configurations. Exploiting these properties may

lead to the development of artificial muscles that may be applied to mimic the movements of animals and insects, and even enable the movement of the covering skin to define the character of the robots and provide expressivity.

2.4.1 Historical review and currently available active polymers

Electroactive polymer technology can be traced back to an 1880 experiment that was conducted by Roentgen using a rubberband with a fixed end and a mass attached to the free end, which was charged and discharged [Roentgen, 1880]. Sacerdote (1899) followed this experiment with a formulation of the strain response to electric field activation. A further milestone was recorded in 1925 with the discovery of a piezoelectric polymer called electret, when carnauba wax, rosin, and beeswax were solidified by cooling while being subjected to a dc bias field (Eguchi, 1925). Generally, there are many polymers that exhibit volume or shape changes in response to perturbation of the balance between repulsive intermolecular forces, which act to expand the polymer network, and attractive forces that act to shrink it. Repulsive forces are usually electrostatic or hydrophobic in nature, whereas attraction is mediated by hydrogen bonding, or van der Waals interactions. The competition between these counteracting forces, and hence the volume or shape change, can be controlled by subtle changes in parameters such as solvent, gel composition, temperature, pH, light, etc. The type of polymers that can be activated by nonelectrical means include chemically activated, light-activated, magnetically activated, and shape-memory polymers, inflatable structures including McKibben muscle, and thermally activated gels [Bar-Cohen, 2001(a)].

Polymers that are chemically stimulated were discovered over a half-century ago when collagen filaments were demonstrated to reversibly contract or expand when dipped in acid or alkali aqueous solutions, respectively [Katchalsky, 1949]. Even though relatively little has since been done to exploit such *chemo-mechanical* actuators, this early work pioneered the development of synthetic polymers that mimic biological muscles. The convenience and practicality of electrical stimulation and technology progress led to a growing interest in EAP materials. Following the 1969 observation of a substantial piezoelectric activity in poly(vinylidene fluoride)(PVDF) [Bar-Cohen, 2001(a)], investigators started to examine other polymer systems and a series of effective materials emerged. The most progress in EAP materials development has occurred in the last 10 years with effective materials that can induce over 300% strains [Kornbluh et al., 2001].

EAP can be divided into two major categories based on their activation mechanism, including ionic and electronic (Table 2.1). Coulomb forces drive electronic EAPs such as electrostrictive, electrostatic, piezoelectric, and ferroelectric. These types of EAP materials can be made to hold the induced displacement while activated under a dc voltage, allowing them to be considered for robotic applications. These materials have a greater mechanical energy density and they can be operated in air with no major constraints. However, electronic EAPs require high

Table 2.1 List of the leading EAP materials.

| Electronic EAP | Ionic EAP |
|-----------------------------------|--|
| Dielectric EAP | Carbon nanotubes (CNT) |
| Electrostrictive graft elastomers | Conductive polymers (CP) (see Fig. 2.10) |
| Electrostrictive paper | Electrorheological fluids (ERF) |
| Electrovisco-elastic elastomers | Ionic polymer gels (IPG) |
| Ferroelectric polymers | Ionic polymer metallic composite (IPMC) |
| Liquid crystal elastomers (LCE) | |

activation fields ($>100 \text{ V}/\mu\text{m}$) that may be close to the breakdown level. In contrast to the electronic EAP, ionic EAPs are materials that involve mobility or diffusion of ions and they consist of two electrodes and an electrolyte. As little as 1–2 V can activate the ionic EAPs, mostly inducing a bending displacement. Examples of ionic EAPs include gels, polymer-metal composites, conductive polymers, and carbon nanotubes. Their disadvantages are the need to maintain wetness and they pose difficulties in sustaining constant displacement under activation of a dc voltage (except for conductive polymers).

The induced displacement of both electronic and ionic EAPs can be designed geometrically to bend, stretch, or contract. Any of the existing EAP materials can be made to bend with a significant response, providing an actuator with an easy-to-see reaction. However, bending actuators have relatively limited applications due to the low force or torque that can be induced. EAP materials are still in research and development and are therefore not available commercially.

2.4.2 A comparison of electroactive polymer actuators and biological muscle

To identify EAP materials that are suitable for the development of artificial muscles, it is best to compare metrics under common conditions. In our search for a suitable artificial muscle technology, we have tested several candidate materials using the same setup and methodology as is used for testing natural muscles [Full and Meijer, 2000 and 2001; Meijer et al., 1999 and 2001]. The details of the experimental setup and actuator design are described by Meijer et al. (2001). The results of these tests indicate that some EAP technologies, like the dielectric elastomers of SRI International [Pelrine et al., 2000], have capacities that lie within the ranges reported for natural muscle. They can generate similar forces and strains (Table 2.2), and work-loop tests indicate that their capacity for doing work and generating power is equal to that of natural muscle (Fig. 2.3). Other EAP technologies, like the P(VDF-TrFE) material (Zhang et al., 1998), outdo natural muscle in terms of force generated, but have a limited strain capacity. As a consequence, actuators made of this material produce very little work. The power output of these actuators could not be tested to their full potential because

Table 2.2 Peak values found in experimental tests. Numbers for free strain are obtained from literature [Zhang et al., 1998; Pelrine et al., 2000; Cheng et al., 2000]. Data for biological muscle is obtained from Full (1997).

| Actuator | Biological Muscle | VHB 4910 Acrylic | CF19-2186 Silicone | P(VDF-TrFE) Unstretched |
|---|-------------------|--------------------|--------------------|-------------------------|
| Cross sectional area (mm ²) | — | 1.26 | 3.76 | 0.170 |
| Preload (g) | — | 150 | 100 | 25 |
| Action upon stimulation | contraction | extension | extension | contraction |
| Strain (%) | 1–100 | 215 ⁽⁵⁾ | 63 ⁽⁵⁾ | 1.2 |
| Isometric stress (MPa) | 0.007–0.8 | 0.60 | 0.15 | 2.15 |
| Max Work output (J/kg) | 0.18–40.57 | 13.17 | 3.19 | 0.25 |
| Max Power output (W/kg) | 9–284 | 35.28 | 20.37 | 0.51 |
| Frequency (Hz) at max power | 1.9–173 | 4 | 10 | ? |

the operating frequency of our setup was limited. It is known that P(VDF-TrFE) materials can work at very high frequencies [Cheng et al., 2000]. Several other EAP technologies, like ionic polymeric membrane metal composites [Shahinpoor et al., 1997] and liquid crystalline elastomers [Ratna, 2001], are currently being examined using similar procedures.

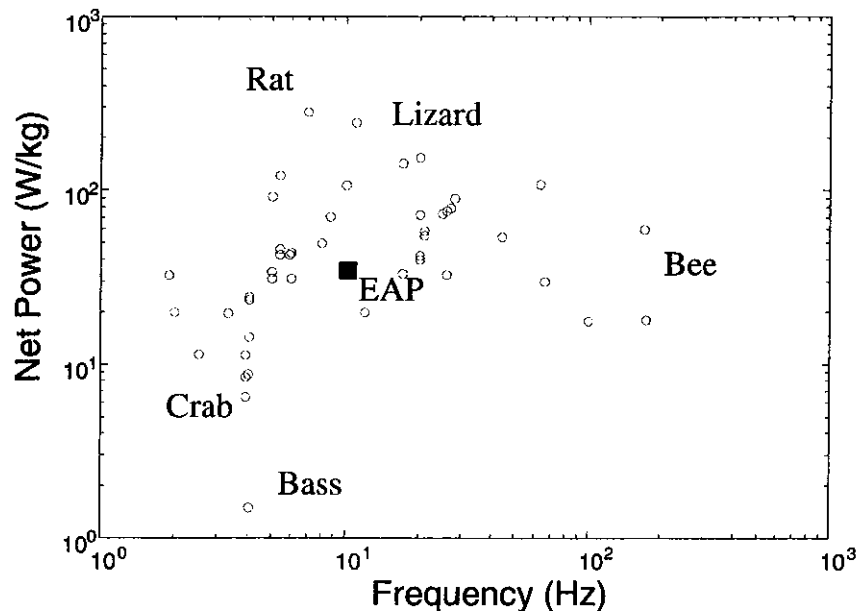


Figure 2.3 Mass-specific power output of muscles [Full, 1997; Josephson, 1993] (circles) and an electroactive polymer (filled square) as a function of the frequency of oscillation. Data were obtained using the work-loop method [Josephson, 1985]. Preliminary results show that EAPs fall within the range of values for natural muscle.

The tested thin-film EAP materials possess characteristics that make them interesting for further development of artificial muscles. However, their performance could be greatly enhanced by more optimal actuator designs. Specific issues that could be overcome by clever designs are (1) of the relatively heavy support systems used by the actuators, most of the designs we tested had unfavorable active mass ratios, (2) the fact that dielectric elastomers extend when stimulated rather than contract like a natural muscle, and (3) the limited strain capacity of certain actuating materials.

2.5 Morphology: Tuned to the Task

Muscle tissue does not have any outstanding characteristics compared to many engineering materials [Wax and Sands, 1999]. It does not develop particularly high forces, large strains, or high specific work output. They do have low densities compared to most engineering materials, making lightweight construction possible. Muscles are successful, not just because of their material properties, but because of the way they are put together. Browsing through an anatomical atlas reveals a wide variety in muscle designs, each having evolved to fulfill a specific task (i.e., power, energy, stability). Structural adaptations can be found at the micro level (i.e., proteins, sarcomeres) as well as at the macro level (i.e., muscle tendon unit, placement in skeleton).

Efforts to develop artificial muscles have focused on creating materials with musclelike characteristics [Kornbluh et al. 2001]. These efforts have led to materials with characteristics that resemble those of muscle (see the previous section), but materials alone do not make a working actuator. Complementing these studies with creative designs may yield useful actuators for biomotion. The development of new fiber- or sheetlike soft materials (see the previous section) that have similar characteristics as muscle might allow for a more biologically like performance.

It is important to realize that muscle function can be only be characterized partially from tests on isolated muscles. The role of their structural arrangement in the skeleton as well as the interaction with the environment has to be taken into consideration. For example, most muscles are organized in flexor and extensor pairs around a joint, which enables them to operate either as a motor or a brake. Furthermore, some muscles span more than a single joint. This multijoint arrangement enables them to act as struts and meet conflicting requirements for movement and force development. In the following sections we will present some of the structural solutions that nature has come up with to meet the functional demands for locomotion.

2.5.1 Reducing weight

Minimizing weight to reduce energy exertion is an important consideration for successful locomotion. Natural muscle has a relatively good energy density. A large percentage of muscle mass, 30–80% depending on the type of muscle fiber, is actually involved in force generation. Muscle is a composite material and it

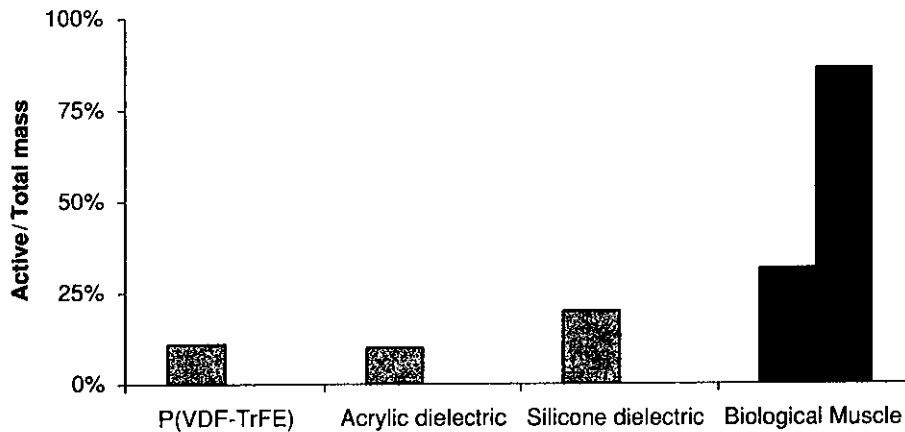


Figure 2.4 Ratio between mass involved in force generation and total actuator mass. Data are shown for three human made actuators (light bars) and two biological muscles (dark bars).

efficiently uses its constituting materials for more than one task. For example, the contractile proteins are embedded in a connective tissue matrix that mainly consists of layers of collagen laid down in a specific pattern [Trotter and Purslow, 1992]. The emerging view in muscle biology is that this connective tissue matrix plays an integral role in muscle-force production. It is not just giving support, but it actually plays an important role in guiding the forces generated by the contractile proteins to the outside world and allowing the muscle to perform work in the environment [Huijing, 1999; Patel and Lieber, 1997].

One of the problems with the EAP actuators we tested is that the materials responsible for force generation make up only a fraction of the total mass of the actuator. For example, the silicone actuator and the P(VDF-TrFE) actuators suffered from unfavorable ratios of 20 and 11%, respectively (Fig. 2.4). These ratios can partly explain the relatively poor mass-specific power output of the actuators. The main cause of the unfavorable ratios is the relatively large mass of the support systems needed to keep the EAP films in tension. Smart actuator designs making use of fiber-reinforced composite techniques [Dowling, 1999] may solve this problem by laying down stiff lightweight fibers in the EAP material. Besides reducing the weight, reinforcement with fibers can also be used to modify the functionality of the actuator. In biological hydraulic skeletons, like sea anemones, fiber reinforcement is used to control shape changes and flexural stiffness [Koehl et al., 2000]. For example, in these animals the orientation of collagenlike fibers in the cylindrical walls determines whether the animal lengthens or shortens when internal pressure increases. We may turn to muscular systems for inspiration on how to design our artificial constructions. Good examples are the McKibben artificial muscles. They shorten when pneumatically inflated because of the way their reinforcing fibers are oriented [Chou and Hannaford, 1996].

2.5.2 Trading force for distance and speed

Some tasks, like cracking a shell, require muscles that are strong, while other tasks, like capturing prey, require muscles that are fast. Nature has modified the basic design of muscle at the micro and macro level to meet such functional demands. The contractile proteins of muscle are organized in sarcomeres, which can be considered the basic functional units of muscle. Muscle fibers comprise thousands of sarcomeres in series, and a muscle has thousands of muscle fibers in parallel. The number of sarcomeres in series determine the distance over which force can be generated and the maximum speed of contraction, whereas the number of fibers in parallel determines the maximum force a muscle can generate.

Invertebrates can tune their muscle performance by changing the sarcomere design [Full, 1997; Vogel, 2001]. For example, the muscles in squid tentacles have very short sarcomeres ($0.9 \mu\text{m}$) that are capable of fast contractions over short distances [Kier, 1985]. On the other hand, the muscles in crab claws have long sarcomeres ($20 \mu\text{m}$) that can generate high forces over a considerable distance [Taylor, 2000]. In vertebrates like humans, sarcomere length is very stable ($2.3 \mu\text{m}$). Muscle performance is tuned by arranging our sarcomeres and muscle fibers in specific ways. For example, hamstring muscles consist of long muscle fibers ($\pm 12 \text{ cm}$; many sarcomeres in series) that run straight along the length of the muscle, whereas calf muscles consist of many short fibers ($\pm 4 \text{ cm}$; few sarcomeres in series) that are at an angle with the muscle's line of work. Although these muscle groups have similar volumes, their function is very different. The calf muscles can generate twice the force of the hamstrings, but the hamstrings can exert that force over half the distance. Besides getting more force out of a muscle's volume, there is one other effect associated with the pennate arrangement of the muscle fibers. In pennate muscles, shortening is partly the result of fiber rotation [Otten, 1988]. This angular effect compensates in part for the reduced shortening, and it also prevents the muscle from getting thicker during contraction. This latter aspect is very important for invertebrate muscles that have to work inside inextensible exoskeletons [Vogel, 2001].

Muscles generate forces that are large enough to power locomotion; however, these forces can be exerted over a range of limited length. Just imagine moving only a couple of centimeters per stroke while swimming. Muscles need leverage to create a distance advantage [Vogel, 2001]. In vertebrates, muscles attach to bony segments at a certain distance from a joint. By keeping the lever arm of the muscle much smaller than the length of the segment, a distance advantage is created by trading force for distance. Ironically, this way of using leverage is very different from the way we use most of our hand tools. There, we trade distance for force to get a mechanical advantage. Soft-bodied animals use a different approach to get a distance advantage. Kier and Smith (1985) noted that, compared to short and wide cylinders, long and slender cylinders elongate more for a given reduction in circumference. Squids use this principle to get amazingly fast and large elongations of their tentacles to catch prey. They achieve this with contractions of the short but fast sarcomeres of their extensor muscles.

The design problems for natural muscle are very similar to those for EAP materials. Many human-made materials face the trade-off between force production and stroke distance [Wax and Sands, 1999]. Some groups are already working on mechanical designs for strain amplification to compensate for the limited strain capacities of their actuation materials [de Rossi, 2001]. Others have developed a range of exotic designs [Kornbluh et al., 2001 and 2002] to explore the possible applications of their material. The development of artificial muscles can greatly benefit from a conceptual framework in which structural solutions are related to functional demands.

2.5.3 Elastic mechanisms

Contractility is not the only determinant of muscle function. Compared to human-made actuators, muscle is considered to be a soft, or compliant, actuator. The visco-elasticity of muscle is another important reason of why muscle is such an exceptional actuator. Muscle fibers act as tunable springs that can set their stiffness depending on their level of activation. In most muscles, compliance is predominantly determined by the elasticity of the tendon. Traditionally, tendons have been viewed simply as the connections between muscle and bone, but detailed biomechanical studies have indicated a much more refined function for these structures.

Animal locomotion—for instance, human running—is a rhythmic activity that consists of a loading and unloading phase. The presence of muscle elasticity makes considerable energy savings possible, by allowing storage of potential energy in the elastic muscle during the loading phase and releasing this energy during the unloading phase. There are indeed examples of muscles that specialize their morphology to maximize energy storage and return; they do so by changing the ratio between muscle-fiber length and tendon length. For instance, the calf muscles of wallabies [Biewener, 1998] have a strong pennate belly muscle, with many short fibers in parallel, which is placed in series with a long compliant tendon. Such a design optimizes the potential for elastic energy storage. Tendon resilience can be as high as 93% [Ker et al., 1988], which means that almost all energy stored in the loading phase is returned in the unloading phase. The muscle fibers in these muscles operate virtually isometrically, functioning as struts for the tendon that takes up most of the muscle length changes. Using muscles in this way is energy efficient for two reasons: (1) isometrically functioning muscle fibers use less energy than muscle fibers that perform work [Kram and Taylor, 1990], and (2) most of the work needed for locomotion comes from elastic recoil of the tendons. Alexander (1992) estimated that in running humans, energy storage and return via elastic mechanisms reduce the work that muscles have to do by half, resulting in substantial energy savings.

In ballistic movements, like jumping, saving energy is of minor importance. For such movements the elastic properties of muscle play an important role in power amplification. For example, during human jumping the Achilles tendon

acts like a catapult. When asked to jump as high as possible, most humans will make a countermovement before actually taking off. During the countermovement, the Achilles tendon is slowly stretched and elastic energy is stored; subsequently during take-off this energy is rapidly released. The rapid release of elastic energy results in an amazing power output of more than 2 kW at the ankle joint [Bobbert, 1986], a value that cannot be reached by muscle contraction alone. Fleas and locusts owe their amazing jumping capabilities to similar catapultlike mechanisms [Alexander, 1992].

The visco-elasticity of muscle also plays a role in the control of movement. Animals negotiating irregular terrains are continuously being perturbed. Controlling such perturbations by means of neural reflexes requires a lot of effort, and, in the case of rapid perturbations, neural reflexes may be counterproductive. Having built-in elasticity can simplify matters because elastic structures respond immediately to any type of perturbation. Muscle has been hypothesized to serve a role in stabilization to rapid perturbations [Meijer and Full, 2000]. Visco-elastic muscle properties may result in stabilizing responses acting before reflexes, therefore termed a preflex [Loeb and Brown, 1996]. Elasticity alone is not sufficient for dealing with perturbations, because of the risk of unwanted oscillations. Damping is needed to prevent oscillations from becoming hazardous. Theoretically, muscle satisfies the visco-elastic requirements for dealing with perturbations, but studies that have tried to characterize muscle as a control element are scarce [Meijer and Full, 2000]. Only recently did Wilson et al. (2001) show that the digital flexor muscles of horses function to damp potentially harmful oscillations of the leg occurring during impact. Their study reveals an important role for a muscle that seemed to be a relic of a structure that had lost its function over the course of evolution, and it supports the hypothesis that intrinsic muscle characteristics play an important role in perturbation control.

Traditionally, human-made actuators are stiff, although recently, elasticity has been incorporated in actuators made with conventional technologies [Pratt, 1997]. Unfortunately, these actuators are rather heavy. The emergence of new actuation materials based on electroactive polymer technologies [Bar-Cohen, 2001] should make lightweight elastic actuators possible. Knowing that elasticity enables the amazing locomotion performance of many animals, it is to be expected that these new actuators will give a large push to the development of legged robots.

2.5.4 Controlling a multisegmented body with linear actuators

Having an actuator is one thing, putting it to work in a multisegmented body is quite another. Legged robots with segmented limbs, which use conventional electromechanical motors to move their limbs, have been disappointingly unsuccessful. Even the most advanced and expensive versions like Honda's P-2 move slowly, clumsily, and are energy inefficient. Legged locomotion brings forward

a whole set of control problems and is a detailed discussion beyond the scope of this chapter. However, two of those control issues are addressed here because they reveal the clever way in which nature finds structural solutions for functional demands.

The first issue relates to the problem of maintaining high-translation velocities with a system of rotating segments. If, in a task like vertical jumping, all segments in a limb start rotating at the same instant, translation speed would quickly decline and power production would be diminished. Legged animals solve this problem by using sequential rotation of their segments. In general, the most proximal segment (the trunk) starts rotating first, followed by the more distal segments with the foot segment completing the sequence. Thus, power is generated by a sequence of joint rotations, for example, hip, knee, and ankle joints [Bobbert et al., 1986; van Ingen Schenau, 1989]. To further enhance power production, power generated in the proximal joints is routed to the more distally located joints. This is achieved by so-called biarticular muscles. These muscles span not one but two joints and they transfer the power generated by monoarticular muscles [Bobbert et al., 1986]. This structural solution to enhance power production is one of the reasons why we can jump relatively high.

The second issue relates to the fact that legged animals exert forces on the environment to propel themselves. For successful locomotion, force must be of sufficient magnitude and with proper direction. The direction of force of a legged system is determined by the distribution of net torques generated at the joints. In many movement tasks there are conflicts between the required joint torques and the required joint movements [van Ingen Schenau et al., 1992]. For example, in cycling, the hip and knee joint extend to push the pedal down; however, during the latter part, flexion torque at the knee is required. If the human leg were to make use of monoarticular muscles, the knee flexors would have to be stretched and absorb energy. Biarticular muscles, especially the hamstrings, provide the solution to this energy problem, by redistributing the net torques such that energy absorption is minimized [van Ingen Schenau et al., 1992].

These two examples show that the development of a true artificial muscle is not only a better actuator in terms of force, strain, and work capacity, but also is a solution for some of the control issues associated with legged locomotion. To understand these issues better we will need physical models operated with linear actuators.

2.6 Concluding Remarks

We are at the brink of a breakthrough in the development of legged mobility platforms with biological performance. Biomotion will not only result in the improvement of objective measures like speed or agility to negotiate irregular terrain, but also subjective ones, like how we perceive a running mobility platform. The latter issue is of importance for the development and acceptance of robots and toys in

our society. Several new developments will facilitate the breakthrough:

- (1) The development of new techniques that allow biologists to study animal locomotion in natural settings will reveal the underlying principles of how they accomplish their astonishing performances [Dickinson et al., 2000];
- (2) the development of novel actuation materials that are lightweight, robust, compliant, and easy to manufacture into various designs [Bar-Cohen 2001(a)]; and
- (3) the awareness among biologists and engineers that they have to work together in this field of biomimetics, and that they need to develop a common language that will enable the development of new hypotheses on how we move [Full and Koditschek, 1999].

A wide range of applications will become available when we succeed to make muscledike actuators [Bar-Cohen 2001(b)]. Legged robotics and biomedical applications, like prosthesis, have much to gain from artificial muscle. It has been argued in this chapter that the development of artificial muscles requires not just materials development, but also an understanding of how design and system integration can affect performance. All of this should be put in the light of the functional demands set by the task that needs to be fulfilled. It is important to notice that the functional demands for an animal may change over the course of its life. Animals have great resilience to such changes by virtue of the adaptive nature of their tissues. Typical examples of muscle adaptation are the ability to regain muscle functionality after trauma or disease and the increase in muscle size in response to increased loading. The development of human-made materials with adaptive and regenerative properties will be the next major challenge for the development of artificial muscles.

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