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Relative planar strain control and minimizing deformation work in elastomeric sheets via reinforcing fiber arrays

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ABSTRACT

This study investigates soft composite sheets that undergo significant deformations. The fiber reinforcement in these systems not only increases the stiffness of sheets like a traditional composite, but also controls the relationships between strains in orthogonal planar directions. Such an ability is useful in controlling the deformation of soft robots, and also enhancing the output of soft actuation techniques like electro-active polymer actuators (also called dielectric actuators). The inspiration for this work comes from squid mantle structures that couple orthogonal components of strain using helical fiber reinforcement. The resulting null space of deformations corresponding to the fiber restrictions creates a family of body deformations that optimize propulsion.

The strain dynamics in the composite sheet are modeled geometrically from fiber orientations, assuming that the fibers are inextensible. After the strain dynamics have been determined, the stress/strain relationship is modeled by considering the matrix and reinforcing fibers to be two separate homogeneous systems interacting through local stresses. Both steps of this modeling technique are validated experimentally showing planar strains in a preferred direction to be as high as 16 times the resulting planar strain of an equivalent unreinforced sheet by forcing negative strains in the orthogonal planar directions. The work required for deformation is derived from the stress/strain relationship by calculating the strain energy stored in the material, and an optimal balance between increased planar strain output and increased material stiffness is analyzed. It is shown that for the specific materials used to create the soft composite sheets (thermoplastic elastomer with cotton fibers) optimal fiber angles lie between 15° and 25° to minimize work required for deformation, but this optimal range will increase with increasing ratio of fiber to matrix modulus.

1. Introduction

Much of the inspiration for this investigation into soft composite sheets comes from observations that fiber reinforcement in soft biological tissues serves a skeletal role, as well as increasing material stiffness [1]. Flexibility is a defining property of propulsion in marine animals [2]. In fish and marine mammals, body shape is dictated by an internal rigid skeleton, and flexible tissues are stretched over the internal structures. However, there are appendages and entire animals that are able to maintain their basic shape without any such rigid elements. Often they rely on systems known as ‘muscular hydrostats’ [3]. In structures such as these rigid skeletal elements are completely absent, instead arrangements of muscles and fibers provide both the forces to drive motion, as well as the support to maintain the desired system geometry. Such systems include elephant trunks and the tongues of various mammals [4] to name a few.

When it comes to soft bodies with no rigid (skeletal) elements whatsoever, there is a trade-off that exists between the possible versatility of the body's movements and high performance of a specialized action. This trade-off exists in biological organisms as well as engineered systems. Here, we summarize, as a prime example, the differences in the mantle structures of squid and octopuses. The mantle is a hollow muscular cylinder surrounding the visceral mass of cephalopods (e.g. squid, octopus, cuttlefish) that is periodically filled with water for respiration and jet propulsion.

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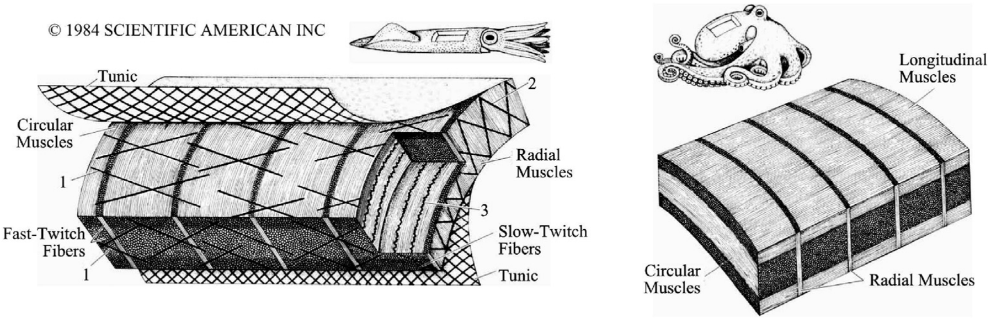

Fig. 1. (left) Schematic of squid mantle tissue dominated by circular muscle fibers with both inner and outer tunics. (right) Schematic of octopus mantle tissue with circular, radial, and longitudinal muscle tissue. Figures taken from Ref. [5].

Fig. 1, which is composed of two figures from Ref. [5], illustrates the structure of a portion of each animal's mantle wall. The octopus mantle tissue is composed of three orthogonal muscle groups, i.e. circumferential, radial, and longitudinal, and by activating these muscle groups in various combinations can deform its body to nearly any shape. This versatility is evidenced by the abundance of complex behaviors exhibited by various octopus, from camouflaging themselves with a combination of changing body shape and using a complex system of chromatophores, to their ability to pass through tiny openings much smaller than their overall body size.

The squid mantle, on the other hand, is specialized to provide the most effective jetting of any cephalopod. Squid mantles are encompassed by an inner and outer shell of interwoven collagen fibers called tunics (see Fig. 1). The tunic fiber angle is surprisingly uniform from squid to squid. Ward & Wainwright [6] observed tunic fiber angles of several specimen of *Lolliguncula brevis* to be at $27^\circ \pm 1^\circ$. If the mantle is assumed to be cylindrical and the fibers to be inextensible, then there is a unique cylinder length and radius for every tunic fiber angle. Vogel, following the example of other studies on helically wound biological reinforcing fibers [7], plotted the volume of the mantle cavity as a function of the fiber angle, showing that for acute tunic fiber angles, a decrease in mantle circumference results in a slight elongation, but a net decrease in mantle volume corresponding to jet ejection [8]. Krieg & Mohseni [1], having noticed that squid only eject a fraction of the total mantle volume during jetting, demonstrated that the rate of change of a cylindrical mantle volume with respect to diameter contraction reaches a maximum when the fiber angle is at $\approx 31^\circ$, very close to the actual tunic fiber angles observed in Ref. [6]. This means that the tunic fiber angles are aligned to provide maximum propulsive jet volume, for a given circumferential muscle contraction. It can be understood in this context that the role of the tunic fibers in the squid mantle is to control the relationship between the circumferential and longitudinal components of strain in the flexible mantle. During jetting the mantle tissue becomes thicker with the decreasing diameter because the tissue resists volume change, and the tissue extends in the axial direction, the relationship between the axial and azimuthal strain being controlled by the tunic fiber angle.

Since the deformation of the squid mantle in the axial direction is limited by the tunic fibers, it does not require longitudinal muscle groups to oppose this extension. As a result, more of the muscle in the mantle can be dedicated to the circular muscle groups providing more power to contract the mantle and expel a jet with higher velocity [9]. In addition, using tunic fibers to restrict deformation of the squid in the longitudinal direction is a passive process, whereas using longitudinal muscle groups to limit extension requires appreciable energetic input. So the tunic fibers also increase the efficiency of the deformation process. Squid mantles also contain an array of flexible intramuscular (IM) fibers that stretch as the mantle wall thickens during jetting, storing elastic potential energy that re-expands the mangle following jetting and thereby aids refilling the mantle cavity [10–13]. The action of the IM fibers, reduces the need for radial muscle groups during refilling, and allows for a further increase in the amount of circular muscle groups driving jetting. It was shown specifically that IM-3 fibers' orientation allows for 90% of the maximum possible potential energy storage [1]. The specialized mantle structure gives squid impressive locomotory capabilities, including the fastest swimming speeds of any marine invertebrate [14,15]. For a more complete summary of reinforcing fiber arrays in biological systems, please refer to [7]. In particular, the discussion about how the fiber angle of reinforcing helical fibers in the cuticles of nematodes and other worm-like organisms controls the stretching of the worm length relative to the contraction of worm width is a concept which is investigated at length in that study.

In a mathematical sense, the trade-off between versatility and specialized performance can be described as a restriction of the deformation space of a soft body. To help explain this concept, consider a system of rigid elements connected by a series of joints. The exact configuration of the system can be uniquely defined by the angle at each connecting joint, meaning that the deformation space of the system has a finite number of degrees of freedom equal to the number of joints. Conversely, a completely deformable body, with no rigid elements, has an infinite number of degrees of freedom. By embedding the soft body with inextensible reinforcing fibers, the original infinite deformation space is reduced to a null space of possible geometries that satisfy the lack of extension in the fibers. The advantages and disadvantages of this process are, as just mentioned with the cephalopod mantle example, that muscles/actuators can be increased in a desired direction, since they are not required to counter deformation in the directions limited by the fibers, but the resulting range of movement is restricted.

The role of reinforcing fibers can go beyond just restricting unwanted deformation, it can in fact drive *negative* strains in unwanted directions to further increase extension in a desired direction. As an example, one common actuation technique used in the field of soft robotics is Electro-Active Polymer actuators (EAPs), sometimes called dielectric elastomer actuators (DEAs), due to their fast response times, high power density, and large degree of flexibility [16]. The basic concept of this type of actuator is that flexible conducting plates sandwiching a layer of elastomer are charged, squeezing the plates together due to capacitive force, resulting in an outward expansion of the elastomer layer by conservation of volume. It has been shown that the performance of EAPs driving motion in a single direction can be greatly increased by prestraining the elastomer layer in the opposite direction [17]. The effectiveness of prestraining EAPs is mostly due to the fact that prestraining