Chapter 2
Soft Mechanisms

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Abstract Actively exploiting material deformation allows for a variety of new mechanisms, from soft actuators to adjustable stiffness. This chapter will organize and describe deformation induced by fluid forces, compliance of rigid structures, and jamming mechanisms. We then provide the definitions and relationships of three typical classes of soft mechanisms: continuum, elastic, and bistable mechanisms. Continuum mechanisms form an important core in soft mechanisms. Elastic mechanisms are useful and can be applied to understanding animal bodies as well as robotic mechanisms. Bistable mechanisms are effective for generating impulsive forces. A basic understanding of these mechanisms is helpful in designing soft robots.

2.1 Deformable Mechanisms

2.1.1 Basic Concepts

A soft mechanism is literally a "soft" mechanism. Soft mechanisms can be broadly classified into two types: those in which the "motion" is soft, and those in which the "structure" itself is soft. In the former case, rotational and linear joints are often connected by relatively stiff links made of metals or other materials. Generally, compliance control is performed to soften the motion of actuators that move rotary and linear joints using one of two approaches: (i) calibrating the joint based on the value of a joint displacement sensor for an electric motor; or (ii) installing an actuator using a compressible fluid, such as a pneumatic cylinder, artificial muscle, or pouch motor, at a position offset from the rotation axis of the joint. In the second approach, the elasticity of the joint is controlled by changing the internal pressure. In

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cases where the “structure” itself is soft, robots are often made of materials such as rubber, sponge, or resin, which are softer (lower Young’s modulus) than conventional materials of high rigidity such as metals. Recently, plastic materials that can produce elasticity as structures (structural metamaterials) have been developed. Moreover, these metamaterials can be modeled relatively easily with a three-dimensional printer or other similar apparatuses.

Although soft mechanisms with conventional rotational joints are also generally available, in this section, we discuss those in which the structure is made of a flexible material.

2.1.2 Basic Function

Two main types of flexible mechanisms exist active and passive. The former type of mechanism converts input energy into useful work using a combination of actuators and structural materials, and its primary functions are force application and support. The latter is primarily used for shape adaptation to the contacting body and for shock absorption.

Spherical, rod, and surface shapes, as well as combinations of these shapes, are used as fingers, arms, hands, legs, wings, and tails for three main functions: to apply force to the object in contact; to support its own weight, and to propel the mechanism by applying force to the environment. One of the main types of spherical actuators uses a fluid to induce deformation and generate force-applying functions. However, deformation can also be performed using electrostatic actuators and other types of non-fluid actuators. Non-fluid actuators, such as Miura folding used for deployable panels, typically utilize an origami structure.

In addition to support by deformation, functions such as suction and retention are also performed by these mechanisms. An example of these functions is the suction cup.

2.1.3 Process of Deformation

Applying force to an object in contact with a mechanism requires the generation of displacement, which, in turn, requires deformation in the soft mechanism. This section deals primarily with fluid-type mechanisms. Nevertheless, principles analogous to those discussed here can be used to generate curving motion from displacement.

Expansion motion

Flexible mechanisms have a continuous flexible structure, which can deform instead of changing its structural angles, unlike a conventional rigid structure with joints. When internal pressure is applied by a fluid, the thin membrane-like structure tries to expand into a spherical shape. If the film thickness is homogeneous, it expands such that the overall diameter uniformly increases. Uniformity is extremely important in spherical mechanisms.

Stretching motion

As shown in Figs. 2.2 and 2.3, the combination of a flexible membrane and stretching constraint provides displacement anisotropy (Fig. 2.1).

In such cases, a two-step deformation behavior is observed, where the tube is deformed, as illustrated in Fig. 2.3, once it becomes cylindrical, depending on whether it is radially or axially constrained.

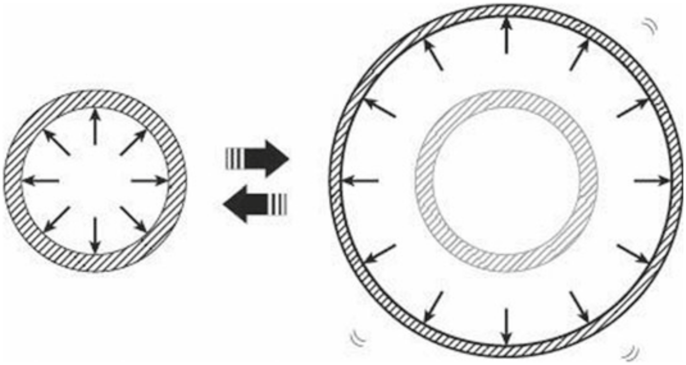
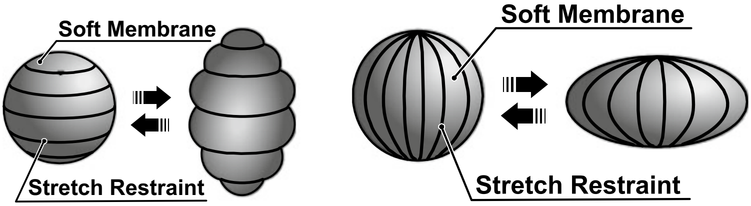
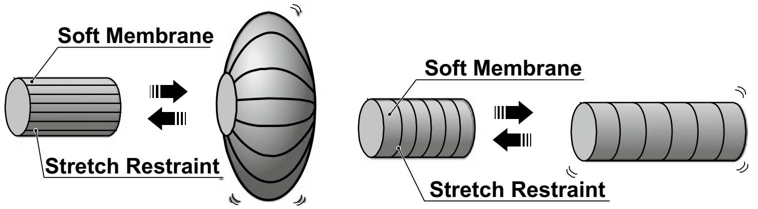


Fig. 2.1 Expansion of flexible membrane due to internal pressure



(a) Radial extension constraint (axial expansion) (b) Axial extension constraint (radial expansion).

Fig. 2.2 Addition of displacement anisotropy in combination with extension constraint in mechanisms such as a spherically shaped fiber



(a) Radial directional extension constraint (axial expansion) and (b) axial directional extension constraint (radial expansion).

Fig. 2.3 Addition of displacement anisotropy in combination with an extension constraint in mechanisms such as a cylindrically shaped fiber

Bending motion

Actuators can be divided into two types: those driven directly by electric motors and rotary joints and those driven by the power transmission of rotary joints. In the latter type, the joints are compact, but the range of motion of the other parts is limited compared to those in the former type.

As is common to all structures, bending and flexion are achieved by inducing relative changes in the physical quantities at geometrically biased positions. Similarly, a change in the physical quantity that induces a large change in the displacement/force only at a geometrically biased position can result in bending or flexion. Conversely, in the natural (neutral) state, the focus is on shaping the object evenly to eliminate bias, or to set the bias of the internal force in the shape and initial state. In addition, fibers or thicker materials are effective in parts of the mechanism that are difficult to deform. The use of these materials facilitates the task of changing the thickness or material in areas that deform easily. Moreover, small actuators that change these high-speed pictures or the physical quantity of the external contact or field can also change the main characteristics of the operation of the mechanism.

The main differences between the various mechanisms are where the actuator is attached and whether it generates an active force in the direction of restoration or passive return.

The most fundamental principle of the flexible mechanism is that the joints are continuously composed of flexible bodies, in contrast to the conventional joints shown in Fig. 2.4. In conventional joints, the extension mechanism is offset from the center of the structure. Moreover, the parts corresponding to A and B in the figure are equivalent in terms of generating bending motion regardless of whether they are exposed or enclosed within the structure. Furthermore, several types of power-transmission methods exist. For instance, Fig. 2.6 illustrates one in which power is transmitted remotely by a wire without an extension mechanism at the position corresponding to A and B. Figure 2.7 illustrates the use of an artificial muscle that fits into A and B. Finally, Figs. 2.8 and 2.9 illustrate a curved structure into which the extension structures are integrated (Fig. 2.5).

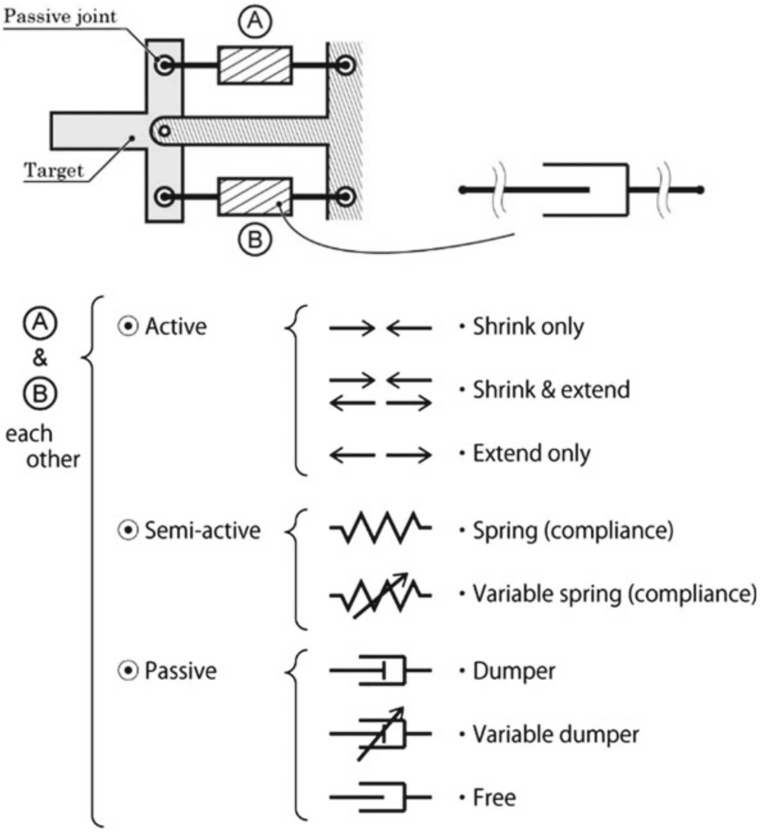
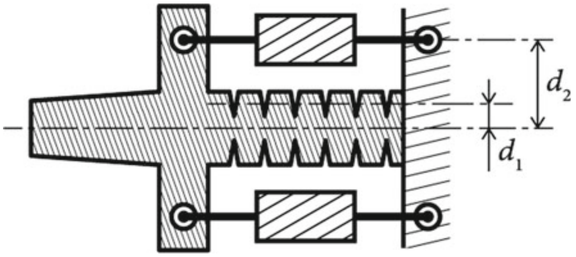


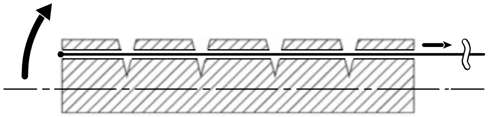
Fig. 2.4 Variable rotational joint system with a conventional rigid structure

Fig. 2.5 Principle of curved motion achieved using a soft structure

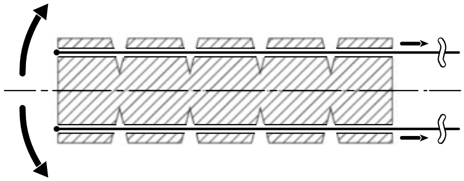


Other structures:

In addition to the abovementioned mechanisms, a torus structure with a propagating tip (Fig. 2.9) and a deformable body with a sponge-like structure inside the membrane (Fig. 2.10) are also available.



(a) One-sided version.



(b) Bilateral version.

Fig. 2.6 Curvature deformation by extending a point offset from the center

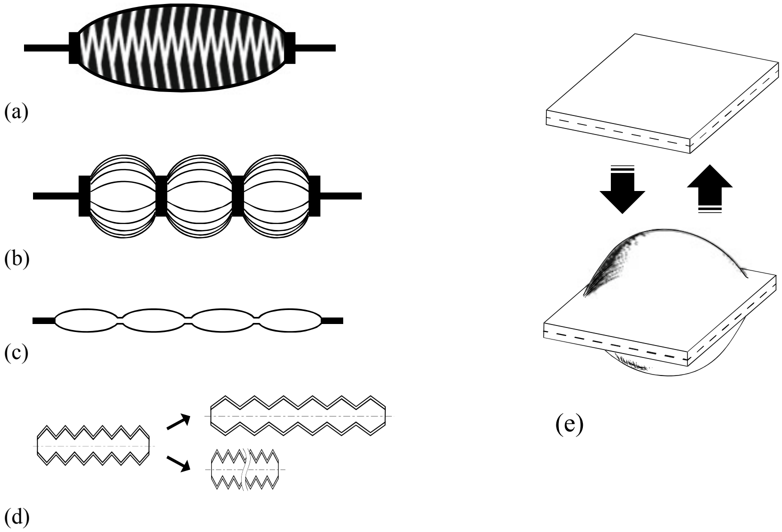


Fig. 2.7 Examples of various artificial muscles. **a** McKibben type (Tondu 2012), **b** Warsaw type (Villegas et al. 2012), **c**Pouch type (connected) (Niiyama et al. 2014), **d**Bellows type (Hashem et al. 2020), **e** Pouch type (single unit) utilizes displacement in the upper direction in the figure

2.1.4 Soft/Rigid Switching

Conventional bag-type flexible/rigid switching mechanisms, as shown in Fig. 2.11, mainly utilize the granular jamming transition phenomenon, in which the powder is sealed inside the closed space of a bag-like membrane. Subsequently, when air, the medium fluid, is removed, the powders jam against each other, resulting in an increase in their rigidity. However, in the case of an elongated bag, buckling tends to occur at its base even in the high-stiffness mode. Furthermore, a structure that generates a stiffness change similar to that induced by the layer jamming transition phenomenon by overlapping multiple plane structures has been proposed. However,

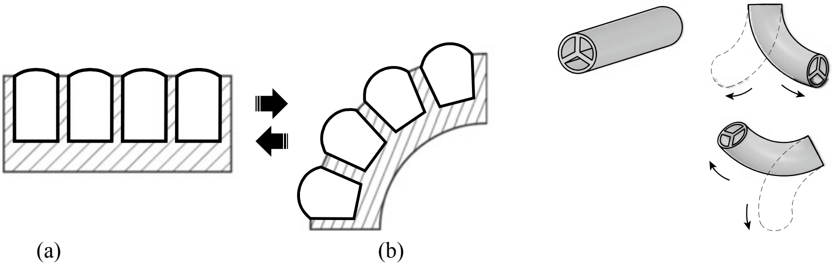


Fig. 2.8 Example of curved displacement generating body. **a** Accordion-type (Mosadegh et al. 2014), **b** 3D curved structure by Suzumori (1989)

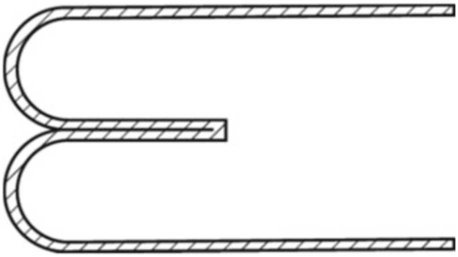
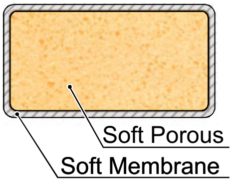


Fig. 2.9 Torus type (Takita et al. 2004)

Fig. 2.10 Combination of membrane and bubble-containing body (Hayakawa et al. 2004)



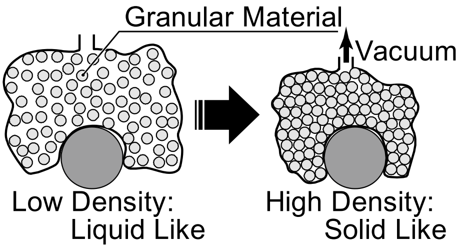
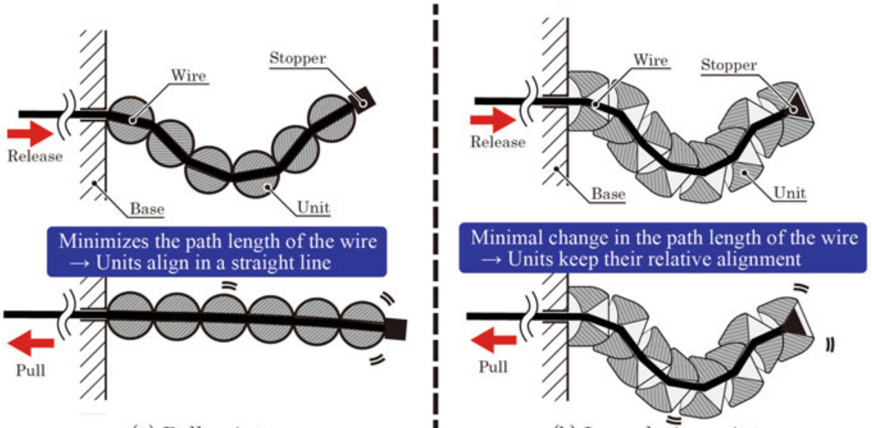


Fig. 2.11 Jamming transition phenomenon

the small bendable radius of curvature in the low-stiffness mode significantly limits the range of motion.



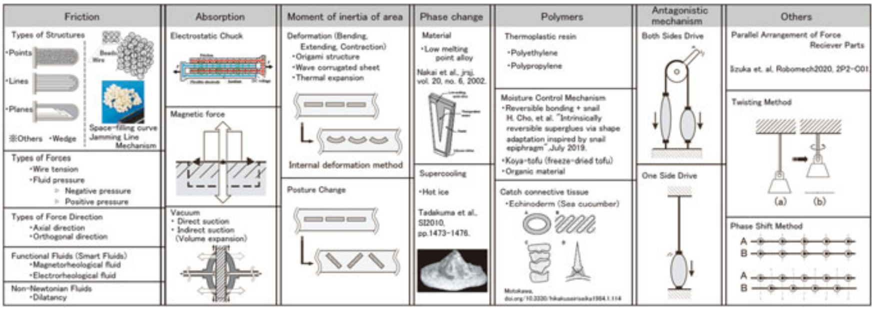
(a) Ball unit type (b) Irregularity unit type

(c) Overview of the prototype model

Fig. 2.12 One-dimensional jamming mechanism

Furthermore, a one-dimensional flexible-rigid switching mechanism that uses wires as elements has been realized in actual devices. This mechanism comprises several units with bead-shaped through-holes and a central wire running through these holes. By applying tension to these central wires, the beads touch each other, resulting in high frictional forces and, consequently, improved rigidity. As shown in Fig. 2.12 (left), a simple spherical bead generates a restoring force to minimize the path length, which impairs the posture.

Table 2.1 Classification of mechanisms for switching between soft and stiff



Friction	Absorption	Moment of inertia of area	Phase change	Polymers	Antagonistic mechanism	Others
Types of Structures ・Points ・Lines ・Planes ※Others ・Wedge Beads Wire Space-filling curve Jamming Line Mechanism	Electrostatic Chuck	Deformation (Bending, Extending, Contraction) ・Origami structure ・Wave corrugated sheet ・Thermal expansion Internal deformation method	Material ・Low melting point alloy Nakai et al., jrsj, vol. 20, no. 6, 2002.	Thermoplastic resin ・Polyethylene ・Polypropylene	Both Sides Drive	Parallel Arrangement of Force Reciever Parts Iizuka et. al. Robomech2020, 2P2-C01
Types of Forces ・Wire tension ・Fluid pressure ▹ Negative pressure ▹ Positive pressure	Magnetic force	Posture Change	Supercooling ・Hot ice Tadakuma et al., SI2010, pp.1473-1476.	Moisture Control Mechanism ・Reversible bonding + snail H. Cho, et al. "Intrinsically reversible superglues via shape adaptation inspired by snail epiphragm" July 2019. ・Koya-tofu (freeze-dried tofu) ・Organic material	One Side Drive	Twisting Method (a) (b)
Types of Force Direction ・Axial direction ・Orthogonal direction	Vacuum ・Direct suction ・Indirect suction (Volume expansion)			Catch connective tissue ・Echinoderm (Sea cucumber) Motokawa, doi.org/10.3330/hikakuseiriseika1984.1.114		Phase Shift Method A B A B
Functional Fluids (Smart Fluids) ・Magnetorheological fluid ・Electrorheological fluid						
Non-Newtonian Fluids ・Dilatancy						

Table 2.1 summarizes the systematization of soft-stiffness switching, including pressurized and wire-traction-type one-dimensional jamming. When configuring the direct-acting jamming mechanism, a two-layer mutual arrangement is more effective than a coaxial arrangement, considering internal wiring. In addition, a configuration that enables flexible and rigid switching in both radial and circumferential directions is possible. This configuration is suitable for multiple joints, which can be driven simultaneously in a simple manner. Another potential method is to change the second cross-sectional moment. This method is an alternative to that of holding by increasing the contact force. However, it requires a design that minimizes the overall dimensional change in flexibility changeover. In terms of practical applications, this method is suitable for paper-gripper mechanisms and soft origami configurations. Another potential method is to place an adsorbent within the device to enclose a negative-pressure-generating organism, magnetic adsorption material, or reversible adhesive material in a fine state.

2.1.5 *Examples*

In the standard jamming gripper, the granular material was packed into the whole bag and the pressing force for gripping is large. In contrast, a hollow gripper shown in Fig. 2.13 utilizes the variable rigid/flexible switching function to arbitrarily change the rigidity of a structure can grip complex shapes and fragile objects without damaging them. In the industrial field, they are expected to play an active role in the assembly of parts and transportation of goods at high-mix low-volume production sites.

An example of a 1D flexible-rigid switching mechanism is the fire-resistant gripper that can grasp even burning objects, as shown in Fig. 2.14. The gripper is torus-shaped with one-dimensional rigid-flexible switching mechanisms discretely arranged around the circumference in the shape of fingers.

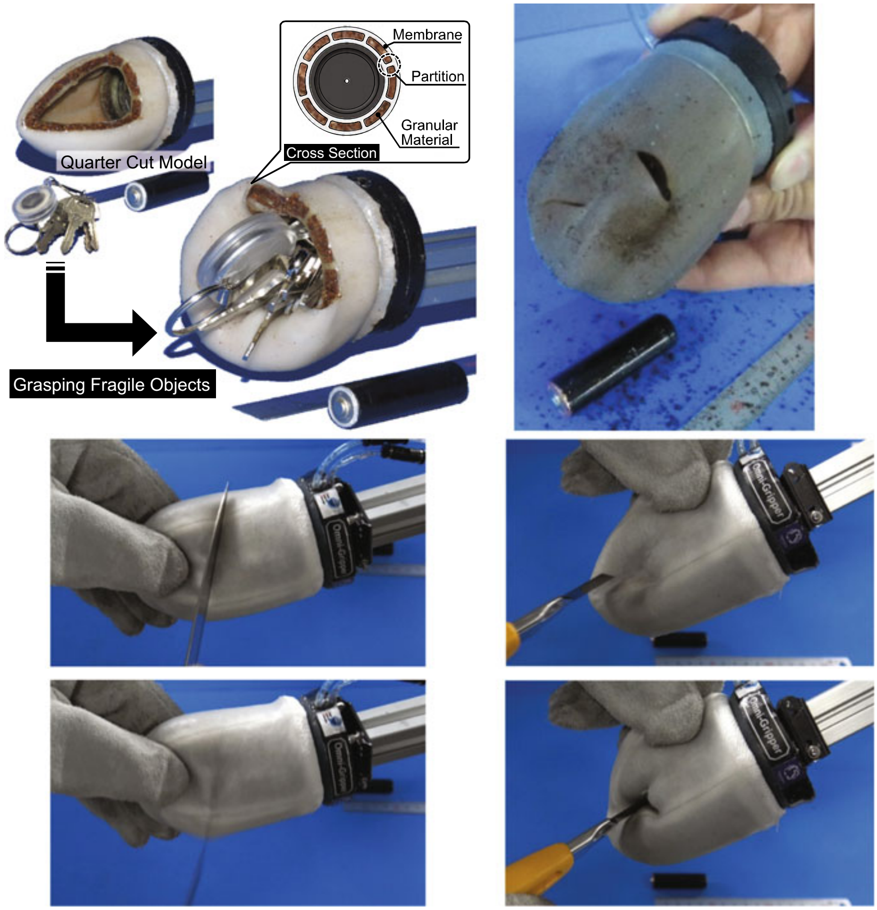


Fig. 2.13 Implementation of flexible-rigid switching membrane gripper mechanism and cut resistance

Flexible mechanisms can be configured to obtain displacement and motion in the desired direction, passively familiarize themselves with the contact object, and effectively apply force by adding a soft-rigid-switching function. In conclusion, these mechanisms have significant potential applications in several fields.

Fig. 2.14 Fire-resistant gripper mechanism equipped with a flexible and rigid switchable linear body (Tadakuma et al. 2008)

2.2 Typical Soft Mechanisms

2.2.1 Continuum, Elastic, and Bistable

In this subsection, the definitions and relationships of typical three classes of soft mechanisms, i.e., continuum, elastic, and bistable mechanisms, are explained.

Continuum Mechanism

Continuum mechanisms consist of continuum bodies that can be characterized by many (approximating infinite) extraordinary kinematic degrees of freedom (DOF). The notion of continuum mechanisms is analogous to that of compliant mechanisms (Howell 2001, 2013) but emphasizes smoothness in shape. For example, the shape of a one-dimensional continuum mechanism is considered as a smooth spatial curve that can be handled by a rigorous geometric model. Although it is possible to consider two-dimensional and three-dimensional continuum mechanisms, most current continuum robots fall into the one-dimensional class. By making full use of their slim bodies, continuum robots are expected to perform useful tasks in narrow spaces that are difficult to access for conventional robots. The term “continuum robots” first appeared in the late 90s (Robinson and Davies 1999), when the term “soft robotics” was not frequently used. Continuum mechanisms form an important “classical” core of soft mechanisms.

Elastic Mechanism

Elasticity is a completely different notion from a continuum. An object is said to be elastic if it deforms when a force is applied but regains its original resting shape once the force is removed. A serial chain of rigid links connected with elastic joints is an elastic mechanism but not a continuum mechanism because its kinematic DOFs are not necessarily large in number. Elasticity is important for robotic mechanisms because the deformation property of elastic mechanisms allows the achievement of “repeated” transformations of mechanisms by using simple actuation devices. Elasticity is also beneficial from a theoretical perspective because elasticity is related to the concept of potential energy. The behavior of elastic mechanisms can be discussed using the useful concepts of equilibrium and its stability based on potential energy.

Bistable Mechanism

Bistable mechanisms are characterized by two stable equilibrium configurations. Each of the stable equilibria of the mechanism is determined by the elastic potential energy of an elastic mechanism. Therefore, bistable mechanisms consist of elastic mechanisms. However, the bistable mechanism is not entirely elastic. If a certain force is applied to a bistable mechanism and the configuration changes from one equilibrium to another, it does not return to its original shape when the force is removed. Elasticity is necessary for generating bistable properties. However, no bistable mechanism can be elastic. During equilibrium transition, a bistable mechanism is necessary to achieve an unstable configuration. This property may be utilized for a quick motion of the mechanism.

Relationship

The relationships among the three classes of soft mechanisms are shown as a Venn diagram in Fig. 2.15. In this diagram, elasticity in a narrow and wide sense is defined. An object is said to be elastic in a wide sense if it includes an elastic object. The word “elastic in a narrow sense” is used here for mechanisms that are elastic. Bistable mechanisms belong to the region “elastic in a wide sense” and outside “elastic in a narrow sense.” Note that important examples of soft mechanisms exist in continuum-elastic or continuum-bistable regions. These examples will be explained in the next section.

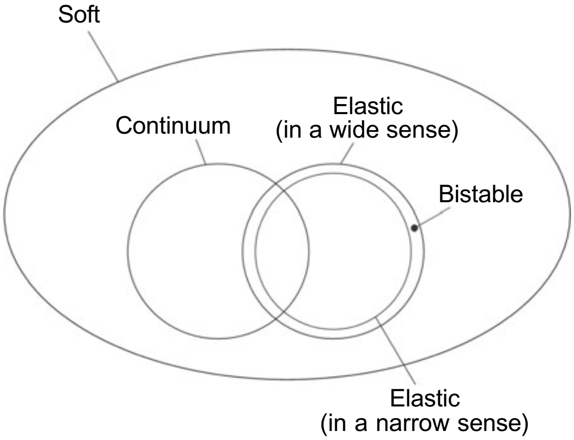


Fig. 2.15 Relationships among the three classes of mechanisms: continuum, elastic, and bistable

2.2.2 Examples of Continuum-Elastic Mechanism

In this section, we discuss four typical continuous elastic manipulators. Continuum-elastic locomotors are described in Chap. 4.

An Elastic Rod Pulled by Wires

One of the simplest continuum-elastic mechanisms is an elastic rod pulled by wires. Consider a straight elastic rod with one end fixed to the ground. Let a wire be attached near the other end of the rod with an offset from the center of the cross-section at the end. Let some guides be attached to the rod so that the wire can move along the rod. The elastic rod is bent by pulling the wire. When the wire is loosened, the elastic rod returns to a straight shape. For spatial deformation, multiple wires are attached near the rod tip in different offset directions, as shown in Fig. 2.16a.

Such spatial deformation mechanisms have been observed since the beginning of the 1980s (Hirose et al. 1983). The mechanism is sufficiently simple, and a slender continuum manipulator can thus be embodied. For example, wire-driven mechanisms have been adopted for steerable/active catheters in medical applications (Ganji et al. 2009). For a more complex deformation, we can adopt a multi-section strategy of connecting multiple elastic rods pulled by wires in series. In this case, wire coupling effects should be considered (Camarillo et al. 2008; Carlson et al. 2009).

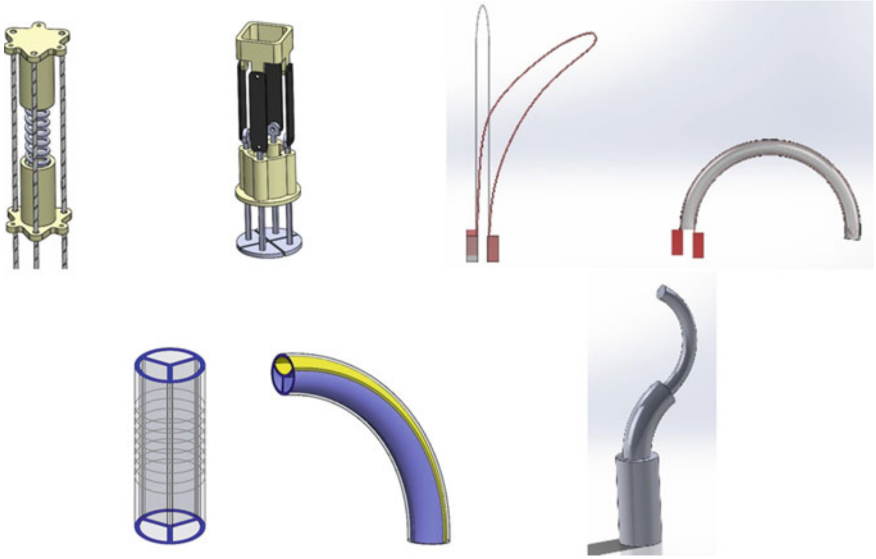


Fig. 2.16 Typical mechanisms of continuum manipulators. **a** Top left: an elastic rod pulled by wires, **b** top center: parallel elastic rods, **c** top right: a sheathed closed elastic rod, **d** bottom left: parallel extensible balloons, **e** bottom right: precurved elastic tubes

An elastic rod can be replaced by a more general viscoelastic object. The recent advancement of wire-driven wearable robot hands is an interesting example (Kang et al. 2016; In et al. 2016).

Parallel Elastic Rods

Two elastic rods are considered. Let one end of each rod be fixed to a linear actuator, and all the other ends be connected to a rigid object with an offset from the center of the cross-section. By pulling/pushing a rod using an actuator, the entire continuum-elastic mechanism ends. When the rod returns to its original position, the shape of the structure also returns to a straight shape. For spatial deformation, multiple elastic rods are fixed in parallel, as shown in Fig. 2.16b. Each end of the rod is fixed to a linear actuator. However, we must be careful about actuation because the inappropriate driving of multiple actuators may generate excessive internal forces. Each pair of opposite rods is driven accordingly. The multi-sections of this mechanism require a nested structure. This makes the entire mechanism large. This mechanism might be useful for adding kinematic DOFs to the tip end of a laparoscopic surgery tool.

The sheathed closed elastic rod has evolved from parallel elastic rods and is shown in Fig. 2.16c. The slender loop of the elastic rod is bent by shifting the end positions of the elastic rods by increasing the loop width. A sheath that covers the loop prevents it from expanding, which significantly contributes to the bending of the entire structure. This advanced continuum mechanism also has medical applications (Yamada et al. 2014).

Parallel Extensible Balloons

We consider three slender balloons, each of which can extend along its length direction by increasing internal pressure. The inside walls of the balloons are sealed with each other. Suppose the shape of the entire mechanism is straight at rest. The mechanism bends by filling air into one balloon, as shown in Fig. 2.16d. The internal pressure control of the three balloons generates spatial deformation. This spatial deformation mechanism was developed in the late 1980s (Suzumori et al. 1992) and is so simple that even a slender manipulator with a submillimeter diameter can be fabricated.

Precurved Elastic Tubes

A complex shape can be formed by inserting a precurved elastic needle into a soft object with rotation. A nested precurved tube can take a more complex shape (Fig. 2.16e). This mechanism was invented for medical use, and the model is described in detail in (Webster et al. 2009, Dupont et al. 2010).

2.2.3 Example of Continuum-Bistable Mechanisms

In this section, snap motors (Mochiyama et al. 2007, Yamada 2007) are described as an illustrative example of continuum-bistable mechanisms.

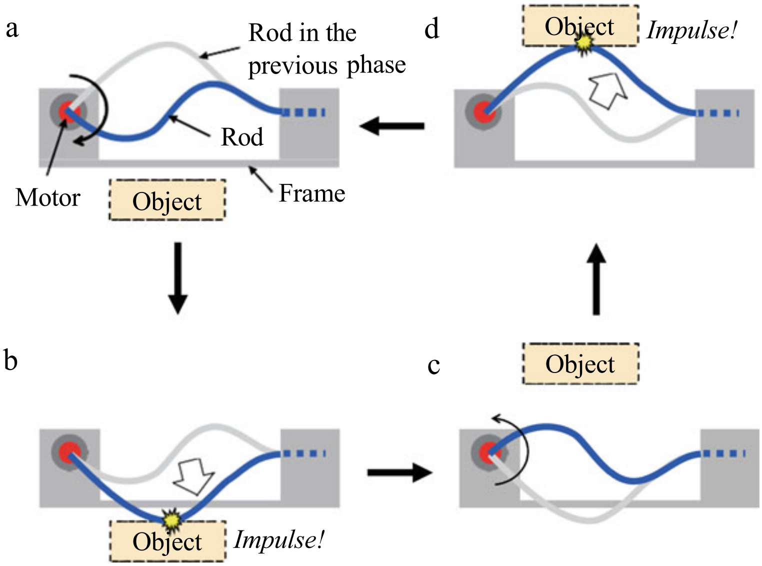


Fig. 2.17 A typical mechanism of snap motors. In this figure, the rod shape in the previous phase is drawn in a light-gray curve

Snap motors are impulse–force generators that utilize a phenomenon called snap-through buckling or snap buckling . A bistable mechanism has two stable equilibrium configurations. Snap-through buckling, unlike simple buckling, is characterized by a sudden change in shape when jumping to the other stable equilibrium configuration through an unstable configuration (Antman 2004). Snap-through buckling can be generated actively by using an actuator. A snap motor is typically represented as a loop mechanism consisting of a large deformable elastic rod, actuator for shape transition, and sufficiently stiff frame, as shown in Fig. 2.17.

In phase A in Fig. 2.17, the snap motor transitions from a stable equilibrium configuration to an unstable configuration by rotating the motor clockwise. In phase B, snap-through buckling occurs; that is, a sudden shape change from an unstable to stable configuration can be observed. In phase C, the snap motor takes a mirrored unstable configuration, as in phase A, by rotating the motor counterclockwise. In phase D, the snap motor undergoes snap-through buckling. Impulsive forces can be generated when the rod contacts an object during a phase shift from A to B or from C to D, where the rod shape changes drastically. This mechanism can effectively generate impulsive forces merely with the repeated motion of one rotational motor. The advantages and disadvantages of the snap motor are as follows:

Advantages

- The mechanism is simple, light, and compact.
- The mechanism does not have any sliding parts. Therefore, it cannot degrade due to wear.

- The mechanism can be repeated to generate impulsive forces with a rather high repeat frequency (about 0.5–2 Hz).

Disadvantages

- The mechanism is difficult to design because its main parts are continuum mechanisms.
- The mechanism is not suitable for generating large impulsive forces because a large elastic rod cannot move quickly due to its large inertia.

2.2.4 Exercises

1. Show some examples of continuum mechanisms and describe the actuators for the mechanisms.
2. Show some examples of elastic mechanisms and describe the actuators for the mechanisms.
3. Show some examples of bistable mechanisms and describe the actuators for the mechanisms.

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