Chapter 2
Motivations

Microscale robots have been around for decades. Soft robots are relatively new to robotics but they have also been on the road to secure their position in the field for at least a decade [1]. So, the fusion of the two in recent years, which gave birth to microscale soft robotics, may seem logical and even inevitable [2]. In the world of technology, however, a mere co-existence of two related fields doesn't necessarily guarantee their marriage. There must be compelling reasons, or motivations, for the researchers to invest their time and effort.

In the case of microscale soft robotics, it is straightforward to see the motivations: the longstanding thrusts to develop robots for clinical interventions and biomedical studies [3]. Over the concerns of safety, those applications impose strict restrictions on both the size and mechanical properties of the devices to be used—The robots must be small and soft, hence engendering the new field of S^3 (*small*, *soft*, and *safe*) robotics [4]. Soon, it became noted that such S^3 robots can bring additional benefits such as polymorphism, re-configurability, and multi-functionality, which immediately constituted another motivation set. This chapter focuses on describing such motivations in a more quantitative detail.

2.1 Small

Conventional robots have been measured in centimeters and meters. Their miniaturization down to millimetric- or sub-millimetric scales, or even towards microscale, has been intensely sought after in robotics for the prospect of hugely widened application scope. Figure 2.1 succinctly illustrates the technological status of "gentle grabbing" of soft objects in robotics. For objects with their dimensions ranging from 1 to 10 μm, such as individual cells, a large variety of devices have been developed and utilized, with the pneumatic micropipette aspirator as the representative example. On the other hand, for objects measured in centimeters and

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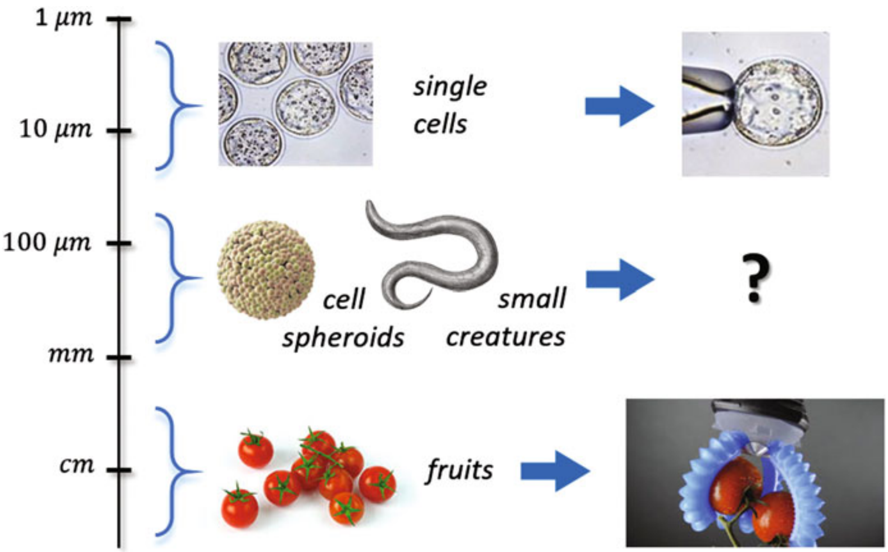

Fig. 2.1 Technological status quo of *gentle* grabbing of soft objects

above, we have started to witness the emergence of various commercial large-scale soft robots. A practical example is the Soft Robotic Gripper from *Soft Robotics Inc.* in Cambridge, Massachusetts, USA, which boasts the capability to handle subtle items such as fruits safely and adaptively as shown in Fig. 2.1. There is, however, a gap in the middle which corresponds to the size range spanning tens of microns to a couple of millimeters. This gap can immediately be recognized as the future battleground for microscale soft robotics.

Traditional examples of other small and delicate objects to be handled gently include small animals, such as the nematode or zebrafish, fish eggs and animal egg cells, and pollens. One important addition to the list in recent years is the cell spheroid. It has stemmed from the realization that neither the conventional, two-dimensionally cultured cells nor the microfluidically isolated single cells can adequately mimic the biological characteristics of the real cells constituting tissues and organs, deterring the intended processes of physiological studies and drug screening. The inadequacy arises from the obvious fact that the cells in truly biological settings are three-dimensionally assembled and networked [5]. In response, many three-dimensional cell culture techniques have been developed over the last decade [6, 7], leading to successful realizations of spheroidal aggregates of cells or cell spheroids. Soon, their efficient and safe handling has emerged as an important issue. The cell spheroids typically measure $<100\,\mu m$ in diameter and are very fragile and sensitive against externally applied stress and deformation. In fact, their dimensions and delicacy render themselves a perfect target for soft robotic manipulation. Seminal results have already been reported [8, 9] with ample potential for future improvements.

One more important source of impetus for microscale soft robotics is their anticipated roles in future minimally invasive medicine in which the diagnostic and operational procedures must occur in remote, hard-to-reach, and highly constrained locations of human body in a non- or minimally invasive fashion. In those cases, the robotic operator must be delivered to the site through catheters or hollow needles and work on highly fragile and subtle objects, such as thin blood vessels or nerve cell for anastomoses or small pieces of tissues for transplanting operations. There the main limiting factor will be the diameter of the catheter and the needle which is typically below a couple of millimeters. All of these have converged into a strong motivation for the realization of *microscale* soft robots.

2.2 Soft

To robots and devices for medical intervention inside the human body, safety always comes as the top priority. For such devices, damaging the tissues around the point of operation is considered a far more serious issue than failing the mission itself. Adoption of soft materials with their compliance levels matched to those of the surrounding biological tissues as the building material of the devices can eliminate the possibility of such problems from the ground up by practically depriving the devices of the capability to damage their biological environment.

For comparing the compliance of materials, one frequently adopts the elasticity, or Young's modulus, E defined as the ratio between the force per unit cross-sectional area and the fractional length increment

$$E = \frac{F/A}{\Delta/L} \tag{2.1}$$

where F, A, L, and Δ represent the axial loading force, initial area, initial length, and the elongation, respectively. As Majidi has pointed out [10], it is apparent from the mathematical form of the formula that the quantity E is only relevant to a prismatic homogeneous object undergoing an axial deformation which is small with respect to its initial length. Nevertheless, the order-of-magnitude comparisons of E values can provide good insights on the issue of operational tissue safety and the scope of adoptable materials since the contact interface between two materials with greatly different levels of E tends to undergo an uneven distribution of force and concentration of stress, causing damages to the softer side which, typically, is the biological tissues.

Table 2.1 summarizes the measured Young's moduli of a few well-known soft materials and biological environments. It indicates that some common elastomers, such as PDMS, exhibit a Young's modulus very close to that of the biological tissues, rendering themselves compliance-matched to biological environments. It becomes especially true for recently introduced elastomers that are

Table 2.1 Experimentally measured E of various materials

Material	E [MPa]	Notes
PMMA	∼2800	From [11]
Polyurethane	10–1000	www.polyurethanes.basf.de
PDMS, hardened	2.3–2.5	Thermally hardened Sylgard 184 from [12]
PDMS, typical	0.7–1.2	Sylgard 184 [13]
Solaris™	0.17	From [14]
Ecoflex™	0.06	From [14]
Human skin	0.42–0.85	Age-dependent [15]
Organ tissues	∼0.001	Liver and muscle tissues [16]

compliance-matched to biological tissues within only an order of magnitude. Good examples include Ecoflex™($E \sim 60$ kPa) and Solaris™($E \sim 170$ kPa) from *Smooth-On Inc.* [14].

Along the progress of the microscale soft robots, researchers have come to the realization that the two motivations mentioned above, i.e., the compactness and compliance, can be combined to produce another point of motivation, i.e., the deformability. In fact, the deformability must be deemed a motivation genuinely unique to *microscale* soft robots, not shared by microscale rigid robots or large-scale soft robots. The latter can be made deformable to a certain extent but it requires huge aspect-ratios in their structures and/or high-power actuation. At microscale, on the other hand, both requirements can be bypassed rather easily, as evidenced by the variety in the available shapes and motions in S^3 robots. More specifically for microscale soft robots, the deformability manifests itself as polymorphic adaptability, dynamic re-configurability, and continuum motion.

Polymorphic Adaptability Soft robots and actuators can transform their morphologies to fit themselves to the environment. In fact, such an ability can be found ubiquitously in the biological world. Figure 2.2a shows one example in which the octopus exhibits its exceptional ability to squeeze itself into a highly constrained space for migration and habitation. A notable example of the capability's artificial replication is shown in Fig. 2.2b. The multigait soft robot developed by Harvard researchers in 2011 succeeded in passing through a gap narrower than its original bodily dimensions by pneumatically squeezing its body to fit the narrow opening. Another example is the retinal pigment epithelium sheet transplanter demonstrated by Konishi and co-workers [18]. The otherwise flat and wide micromanipulator can be pneumatically rolled into the form of a thinner cylinder so that it can be inserted through a narrow, hollow needle.

Dynamic Re-configurability With judicious choice of the shape, dimensions, and material composition, the polymorphic adaptability can be pushed to the extreme, to the point of giving not just a new shape but also a new functionality to the robots and actuators. Such a dynamic re-configurability has been highly sought after in soft robots as a prerequisite for realizing on-demand multi-functionality. Regarding this aspect, the soft micromanipulator shown in [18] can be another example since the

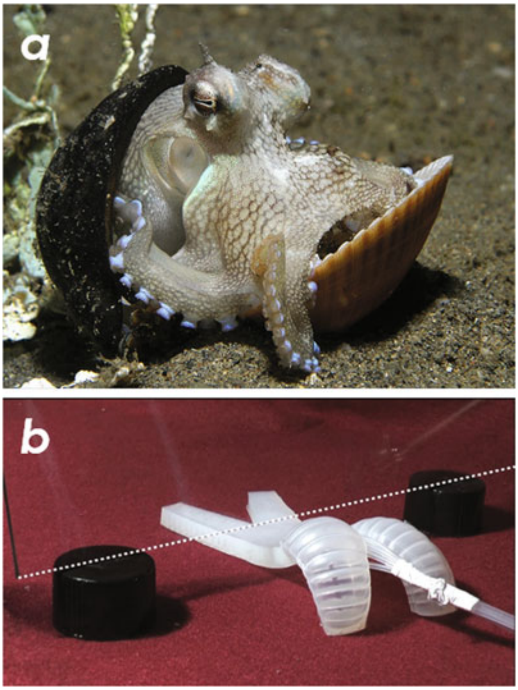

Fig. 2.2 (**a**) An octopus can squeeze itself into a shell much smaller than its body for habitation and migration (Image from *Wikimedia Commons*). (**b**) The *Multigait Soft Robot* from Harvard University [17] can squeeze itself through the narrow gap underneath a glass panel (Photograph courtesy of George Whitesides Laboratory)

cylindrical rolling motion, an extreme case of utilizing the deformability, also allows it to function as a gentle grabber (and also a releaser) of delicate planar structures, such as tissue sheets.

Continuum Motion Beyond the three aspects described above, the adoption of highly deformable and stretchable materials for building robots and actuators can also greatly simplify their design and implementation. It is straightforward to see that most rigid robots and actuators are articulated, with a finite number of bending/twisting joints providing the motion capability. Internally, the joints consist of hinges, fixtures, and friction-mitigation mechanisms meticulously assembled and fitted for proper operation. Such a level of sophistication gets increasingly difficult to achieve or justify as the overall dimensions decrease. Deformable material-based actuation can ease the complication by enabling joint-less, continuum-based motions, as will be described in the following chapters.

2.3 Safe

The compliance of the material also limits the maximum level of force to be exerted by the actuator made of it. According to Shimomura et al. [9], typical biological tissues in the form of multi-cell aggregates can withstand up to 1 mN of force.

For microscale actuators made of highly compliant materials like PDMS, such a force level is hard to achieve since the actuator body itself becomes deformed and recedes before it could exert force exceeding the critical level. For example, the author's own work of microscale PDMS tentacle actuator [19] turned out to apply only sub-mN level force. It became maxed at 0.78 mN under 10 psi pneumatic pressure, which is only one order of magnitude higher than the muscle force of a *C. elegans*, a common nematode [20]. In fact, many of the soft actuators are excessively compliant to the point of frustration for some practical applications, such as intra-vascular navigation, prompting researches to develop switchable schemes for stiffening the actuators.

In recent years, human friendliness has arisen as an extra point of motivation in the field of robotics. It came from the need to make the robots maximally suitable for interaction with humans, especially those who are under/over-aged, handicapped, or undergoing clinical cares. In those situations, the rigid, inorganic look-and-feel of the conventional robots can estrange the potential users, leading to a reduction in their use and effectiveness. In fact, the entertainment community reacted most quickly. For instance, *Pixar Studio* has premiered a highly futuristic, totally soft-bodied robot *Baymax* in 2014.

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