Intelligent Liquid Integrated Functional Entity: A Basic Way to Innovate Future Advanced Biomimetic Soft Robotics

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1. Introduction

Modern robotics emerged from the manufacturing industry in the 1950s. After a rapid development over half a century, the extremely rich applications of various advanced robots have become a brilliant achievement of human civilization, which, however, are mainly rigid robots so far. Such systems commonly feature a fixed structure to serve a specifically constant goal, based on solid metallic materials for longer use lives, whereas the flexible adaptation for various conditions is not emphasized. Usually, the more advanced capacity the robot owns, the more sophisticated the structure will be, let alone the complexity of manipulation, which actually limits the versatility for more working occasions. For a long time, tremendous efforts have been kept making to imitate human or other animals’ form aiming for enrichment of robotic functions (Figure 1a,c). But unfortunately, the usually realized stiff behavior pattern is overall inferior compared with those of animals’ ingenious talents, which is basically a soft entity (Figure 1b).[1]

The soft robotics originated from the inspiration of some typical kinds of mollusks, with significant differences from those rigid ones. Compared with the rigid robots, missions for developing soft ones lie in the vision that it will significantly simulate advanced characteristics of animals, such as the nimble athletic ability, and even acquire versatility for various tasks. For such a purpose, materials with low Young’s modulus or deformability, such as polydimethylsiloxane, electroactive polymer,[7] shape memory alloy,[8] shape memory polymer,[9] and dielectric elastomer,[10] have been used to acquire large-scale deformation of the whole robotic structure. Strategies on actuation are far beyond traditional mechanical drives, which have been mainly electrically propelled. Unusual materials on soft robotics have inspired novel ways, such as direct pneumatics,[11,12] jamming effects,[13,14] chemically based combustion or gas production,[15–17] electrical field or electrically induced...
motion,\cite{18-20} and magnetic field,\cite{21,22} the choice of which is closely related to the material itself. To date, a series of representative soft robots have come out; however, the distances from laboratory test to factory use are still large. Besides the deficiency of technology, a deeper cognition of soft robotics and more universal thoughts about design are urgently needed. There certainly exist several fundamental issues, such as the motion theory of a soft structure, the actuation strategy of a soft system, the optimization of flexible materials, and the intelligent control, which are all in great needs of profound considerations.

Inspirations could be expected from nature considering an obvious distinction between manual machines and natural creatures, which refers to the using of liquid elements in a structure (Figure 1e). The fact that the animal features a quite high mass ratio of its body would indeed make a difference. The body fluid system is well known to diffuse in all parts of the body and collaborate for various physiological processes. There have been a great many mature studies emphasizing the profound effects of these liquids in keeping the internal milieu steady, focusing on their functionalities as to physical interaction, information transfer, thermoregulation, chemical reaction, immunity, and so on. But simultaneously, the liquid can participate more directly in deformation or motion of creatures, such as stomata guard cells in flaccid/turgid states and jumps of the spider. Overall, the functionality of the liquid is far beyond what we understand before, which potentially may open a new world for the development of future highly advanced intelligent soft robots. In fact, the liquid had ever been used in the structure of rigid robots for cooling and hydraulic power (Figure 1d), although its generalized importance for innovating robots is not well understood. We believe that given sufficient investigations, it would play an even bigger role in future soft robotics, which has similar materials with animals.

In this article, we conceive that a most basic restriction of current soft robots may come from the inclusion of intelligent liquid, and our effort tries proposing a perspective conjecture that the liquid should be treated as a critical system to conduct multiple functions for the future advanced soft robots. This methodology with generalized purpose can be named Intelligent Liquid Integrated Functional Entity (I-LIFE). The short term I-LIFE as abbreviated here also refers to the technological goal that the functional components thus realized should behave as close as the capability a living system generally owns. In particular, this article aims to systematically explore the intelligent potentials of liquid in artificially made machines, based on those inspirations from nature. Several promising smart liquids are therewith suggested as the currently available candidates although more fluidic materials can be explored in the near future. The formidable scientific and technical challenges encountered are interpreted in the last. It is expected that the basic principle of the robotic I-LIFE system would inspire many worthy directions for future studies in developing ever advanced soft robotics.

2. Robotic Roles of Intelligent Liquid in Nature or Artificially Made Systems

To illustrate the conjecture of liquid for future design of soft robots, a group of typical convincing evidences were outlined primarily. Several conceptive inspirations, in fact, originate from natural creatures, which have also implemented academic or engineering applications. Clearly, not all the functions of liquid inside the body can be instructive for developing human’s desired soft robots. Consequently, we screened out the following five aspects of liquid’s potentials in brief (Figure 2), which we believe rank in the first place at this stage.

2.1. The Relationship between Intelligent Liquid and Locomotion

From an indefatigable automated machine initially to a manual intelligent worker now, the applications of robotics have been vastly expanded to a degree where it is hard to roundly summarize its capabilities. The competence of motion is universally recognized as a fundamental one of top priority. To get a robot move continuously requires an integrated multifunctional system...
referring to the actuation mode, the power transformation, the balance control, the attitude perception, and so on. In the current development of soft robotics, the liquid is rarely considered as a helpful participator. As a remedy, this section will address its potentials along this direction.

2.1.1. Hydraulic Actuation Strategy

For traditional rigid robots, their moving parts usually feature fixed shapes made of tough materials, so the rigid body kinematics are qualified enough to guide specific designs. However, the wide usage of elastic materials for biomimetic purpose of soft robotics leads to a totally different strategy, which has been a mainstream style in current development. Such soft structures are usually driven by the deformation of functional parts, which is motivated by an inner pressure change of selected cavities. The compressed gas is a common choice which has been successfully applied in various pneumatic actuators. Besides the convenience of design and preparation, when the gas is charged into cavities, the low-density characteristics will only cause tiny weight perturbation.

Compared with the gas, the higher density liquid is more likely to influence the mechanical stability of the structure when it is largely imported inside to inflate the cavity, so a multi-pneumatic-chamber design may not be suitable for liquid. However, the incompressibility of liquid illuminates another
available path via hydraulics. A pressure change can realize an undiminished transmission wherever it occurred in the fluid. Therefore, an actuation strategy can be supposed by the stress transmitted in the liquid. In fact, such a hydraulic pattern has played a key role in animals. For instance, the blood can be applied in specialized tissues to cause engorgement, resulting in an erection of these tissues (such as penis and clitoris). Another typical case is about the spider (Figure 3a–c), whose legs lack muscles strong enough such as locusts. During its jumping, the hemolymph is forced into its legs under pressure and causes them to straighten for a powerful jump. The body fluid directly contributes to deformation or motion of soft organs via hydraulic power in these cases. Therefore, the liquid can have the potential to serve for actuation of soft structures.

2.1.2. Dynamic Balance Control

The mechanical equilibrium is an extremely vital foundation for all kinds of locomotion. Static balance is a typical state easy to achieve, whereas the dynamic balance appears more commonly existed in nature. Facing environmental changes and disturbance at any moment, every natural creature features accurate control of dynamic balance for its body. Such a precise dynamic control strategy is also a fundamental issue for many advanced robots. The profound breakthrough, such as Atlas made by Boston Dynamics, represents the top level of balance control that humans have ever approached, behind which there are highly complicated algorithms, sensitive sensing elements, and proper structure design. Deforming continually under an applied shear stress is the significant characteristics of liquids. When contained in a vessel with a free surface, the liquid will interact freely with the walls induced by movements of the vessel, thus influencing the system dynamics markedly. Therefore, for those large-size containers with mechanical equilibrium needs, the existence of the liquid is more regarded as an unfriendly troublemaker, with a probable induction for instability. Subjects, such as sloshing dynamics, were raised to meet the challenge of liquid, where the designs for tank vehicles or aircraft tanks are typical cases of applications (Figure 3d). However, the flexibility of mass adjustment for liquid and flow characteristic can amazingly enable it to participate in a balance control. A tuned liquid damper (TLD) is a typical facility to resist the undesirable vibration of skyscrapers caused by earthquakes or blustery winds, which is exactly in virtue of the sloshing of liquid in a solid tank. The vibration energy is dissipated by the friction of boundary layers, contamination of free surface, and wave breaking (Figure 3e). The successful applications of TLDs reveal some unique advantages of liquid-involved balance control, such as lower cost, more sensitive responses to small perturbations, and easier adjustments of the operating condition even after installation.

As for animals, the endolymph inside vestibular apparatus of ears can serve as motion receptors, offering us another typical participation mechanism of liquid for robotic equilibrium control. The semicircular duct has a crista with a cupula attached, and the ampulla contains functional endolymph (Figure 3f). When the head rotates toward one direction, the cupula and hair bundles will be bent due to the responsive inertial drag of inner endolymph, thus triggering potential variations and conveying information to the brain for subsequent control (Figure 3g). Meanwhile, the three semicircular ducts are perpendicular with one another in three planes, the delicate arrangements of which enable effective detections of rotational acceleration or deceleration. In addition, experiments about relationship between blood and body balance were ever conducted by Conforto et al. The blood is a typical kind of non-Newtonian fluid, for which it maintains the ability of smoothly flowing with different velocities. The continuous fluidity accompanying physiological activities can bring a significant impact on mechanical equilibrium. Although no more studies toward this issue are available so far, we believe that the blood is more likely to play an active role in balance control rather than passive response as TLDs. In particular, the effectiveness of dynamic balance control largely lies in the assessment of current state, the design for next equilibrium, and the execution of relative moving parts. The variability of liquid in dynamics can represent an available potential for quick altering in reverse, and adjustments can be skillfully realized through actions of small amounts of flowing liquid, instead of a whole-body movement.

Based on the aforementioned analysis, the liquid owns a potential to actuate soft robots hydraulically, and it may be used for balance control of robots with proper flux and precise flowing design. The first potential has been proved by several specific biological tissues, and engineering applications are universal as well, thus the key problem lies in the available biomimetic design for soft structures. As for the second conjecture, believable verifications needed, whether the liquid can function as expected is still unclear. However, it certainly is an interesting and worthwhile idea.

2.2. An Efficient Distributed Energy System with I-LIFE

Efficient supply of energy has been a fundamental request for both natural creatures and artificial machines. Animals feature biochemical reactions performed at anytime and anywhere in body, whereas electrical power assumes an overwhelming demand for most manmade facilities including rigid robots. Different forms of energy supply have their own merits, but a more obvious distinction is the distribution pattern. Cells are the basic units of energy supply throughout the biological body, and they are surrounded by various kinds of liquids which are responsible for accurate transportations of raw materials and products. Consequently, a highly distributed energy system with clear division is formed. In contrast, manmade machines often prefer a centralized energy system for the convenience of design, control, maintenance, and high efficiency. Although the distributed system has theoretically higher tolerance for risks, it will place severe demands on the reliability of every single equipment. For rigid robots, traditional centralized electrical supply, such as internal batteries or external sources, can ensure high power and high efficiency, which can easily bear a heavy load with acceptable cost. Therefore, adjustments about the distribution mode for rigid machines may be not actually necessary. However, the emergence of soft robotics boosts several available strategies of energy generation. With the desired adoption to variable unknown environments, reliability of energy supply for soft robots needs further consideration.
Figure 3. The analysis of liquid-involved locomotion and engineering applications. a) Channels in the tibia of spiders, which provide the rapid transport of the hemolymph during the movement of joints. Reproduced with permission. Copyright 1985, Springer Nature. b) Mechanical bauplan of arthropod legs where the muscle forces and hemolymph pressures both affect loading situations of segments. Reproduced with permission. Copyright 1985, Springer Nature. c) Torques developed by hemolymph pressures. Reproduced with permission. Copyright 1985, Springer Nature. d) A 3D simulation schematic of liquid sloshing in the fuel tank. Reproduced with permission. Copyright 2014, Elsevier. e) Mechanisms of the tuned dampers. Copyright 2012, John Wiley & Sons. f) Schematic details of the inner ear where endolymphatic fluid is colored in black, perilymph in white, and temporal bone in grey. Reproduced with permission. Copyright 2017, Institute of Physics Publishing. g) The participation mechanism of endolymph in equilibrium. Reproduced with permission.

TMD: Tuned Mass Damper
TLD: Tuned Liquid Damper
Generating energy chemically has been practiced successfully among those novel ways,[15,16] somewhat like the biochemical method. Nonetheless, those several typical examples based on chemical-reaction energy have common imperfections, such as quite small volumes and finite forms of available motion. Such drawbacks may blame the energy supply mode, for the spread of contributing chemical effects, such as gas expansion, explosion and combustion is largely restricted because of the fixed reaction chambers and limited dose. Therefore, if reactions can exactly occur where it needs to execute motor function, the energy produced will be more efficiently consumed.

Following such an idea, we can explore a brand new potential of intelligent liquid in soft robotics. A distributed system requests effective control for reactions conducted in assigned places, for which liquid is qualified. It is known that a multicomponent reaction can be controlled through altering the dosage of one specific reactant, and the fluidity of liquid gives it advantages for flexible contact and quantity adjustment. Therefore, if a liquid–solid reaction is used for energy supply, the liquid reactant can be used to regulate both the start/end and output of the reaction. In the non-working state, the liquid reactant can be centrally stored in one chamber to simplify the structure. Consequently, an energy supply system with centralized storage and distributed reaction is available, based on a delicate fluidic system. In the view of energy production competence, the carrying of various particles in body fluids enables a variety of biochemical processes to serve specific physical activities. The solubleness of liquid for different solutes enables an active medium that is accessible for more reactions simultaneously. The existence of a liquid environment will benefit a lot for designing and manipulating chemical energy production where more available strategies need exploiting.

In a nutshell, the energy supply mode via chemical reactions is the very one, which has the potential to realize self-actuation for soft robots. In addition, the idea about developing a liquid-based distributed system really has practical values, which may further improve the energy efficiency and increase the independence of action parts, eventually helping make normal-sized soft robots.

### 2.3. The Potential of Using Liquid to Tune Physical Performance of I-LIFE

The choice on materials is a fundamental difference between rigid robotics and soft robotics. Stiff materials would ensure the durability of machines, which is necessary for frequently used and easily damaged occasions, but they may pose a safety threat to users in operation oppositely. For some quite delicate tasks, such as picking up an egg, such machines have to act slowly and clumsily to avoid destruction. Although more complicated control programs can be applied to optimize operations, the unavoidable rigid material seems to be a congenital deficiency.

Soft materials, such as the silicone elastomer, as applied in soft robotics are inspired from those soft biological tissues, which generally feature low Young’s modulus. Progresses have been made in large-scale deformation, motion of high degrees of freedom (DOF), and soft gripping for soft robots. However, the lack of essential stiffness about soft materials has locked the imitated objects in a limited scope of simple mollusks, whereas vertebrates with more advanced forms of motion are quite difficult to follow.

The human body comprises a variety of materials from the soft tongue to hard bones, with the Young's modulus varying from $10^{-3}$ to $10^5 \text{ kPa}$ (Figure 4a), and some special tissues can perform characteristics of variable stiffnesses. Such a delicate combination of different biological materials actually has an impact on posture maintaining, motion, specific behavior, and so on. For instance, studies have proved that regulating the stiffness of each leg could develop a better performance compared with sole control of the gait,[37] which aims to maintain a nearly similar running mechanism on landforms of changeable rigidities.[38] Apart from this assistance for motion, the specialty of variable stiffness can directly motivate actuation for soft structures via controllable deformation. In 2019, Must et al. designed a variable-stiffness tendril-like soft robot inspired by the osmotic-driven reversible turgor of plant cells (Figure 4b–e).[16] Therefore, such a regulatory mechanism is of practical value for soft robotics.

From the foregoing, the ideal materials as applied in soft robotics must be a combination of stiffness and softness, and preferably rigidity-adjustable. Enriching properties of soft materials thus has become a hot topic, one typical example of which is the design strategy for multifunctional hydrogels.[23,39] However, for most commonly used silicone elastomers, properties have been changeless because they are compounded, so methods oriented these materials are of more realistic needs. Efforts were made to attach a variable stiffness endoskeleton made of low-melting point alloys to an elastic pneumatic bending actuator, successfully achieving multipoint bending and shape retention (Figure 4f), which is a meaningful trial for realizing a whole structure with variable stiffnesses.[12]

The arms of human body may provide inspirations, which basically comprise rigid bones, elastic muscles, soft skins, and blood flowing in the tiny vascular network. In some cases, these soft tissues are actually stiffness-changeable, such as tension and relaxation of muscles, which shows an obvious quick variation of rigidity. For the physiological mechanism, this process is related to the liquid absorption of cells, which reveals that the liquid can help adjust the rigidity of a compound material system. A quite similar case is that different postures of plants can alter with the help of internal liquids. The stiffening and simultaneous rotating motions of the tendril-like soft robot mentioned earlier were exactly based on the transmission of electrolyte solutions. Therefore, the liquid can be a promising candidate to regulate the stiffness of a whole structure.

Although it is possible, the distribution of liquid in a vascular network represents an extraordinary order and enables smooth interaction with the cells, the autonomous selective permeability of which facilitates transport of liquid. Such a structure reminds us that simply adding water into materials cannot function as expected. To fulfill a reversible, highly responsive liquid-based stiffness adjustable structure, two possible strategies can be proposed. One focuses on the direct interaction between functional materials and liquid to imitate behavior of cells, which may refer to accessible mechanisms, highly controllable membranes, and sensitive adjustment, whereas another relies on a flowing network made of soft tubes dispersed in the whole structure, manipulating liquid to fulfill stiffness-variable skeletons. Each of them has its own advantages and disadvantages, and each deserves further consideration.
2.4. A Sensory System with Intelligent Liquid Participation

In nature, noticing surrounding variations sensitively and quickly responding to possible threats ensure animals survive in a dangerous world. A physiological sensory system is mainly composed of visual, auditory, vestibular, somatosensory, olfactory, and gustatory subsystems, which can be triggered via a multitude of external or internal stimuli. Besides the excellent capacity of sensory cells, an incomparable characteristic of biological systems is the numerous active sites distributing throughout the body, such as the mechanoreceptors free or encapsulated in the human skin (Figure 5a).

The sensory system is a vital component of robotics as well, but there is no need to establish a comprehensive system to capture as many kinds of signals as animals do, technologically infeasible likewise. Detecting information to assist motion and interaction control is actually enough for manmade robotics at this stage. For rigid robots, vision, location, velocity, acceleration, and force are confirmed as five essential signals, for which various high-performance sensors have been well developed. As for the arrangement of sensing devices, the mechanical analysis for rigid structures can help figure out global parameters via signals from several critical sites. Therefore, considering the availability of sensor integration, work efficiency, and expense, setting a few sensors at key positions is enough to satisfy the sensing needs for most rigid robots. Comparing the differences between manmade sensors and natural ones, installing them on a robot from head to toe is not feasible and not necessary.

However, situations are different for soft robotics. Due to the nonlinear and even more random deformations and motions of soft structures, the classical mechanical analysis is almost unable to get parameters theoretically, and restriction on rigid sensors is also an obsession. In addition, selecting an appropriate physical index to represent flexible motion is a more fundamental issue. Efforts are made to deal with these problems. The curvature is chosen as a promising feature to describe actuations of soft structures, and available products have been applied as an optical curvature sensor (Figure 5b). Simultaneously, a piecewise constant curvature (PCC) model with necessary simplifications is proposed for the kinematic mechanism of continuum soft robotics, in support of the curvature sensing method. Recently, a novel stretchable dual-capacitor multisensor was fabricated which will have a better potential to be applied in soft robots (Figure 5c).

In short, an effective sensing for the continuous, complex, and compliant motion of soft robots is a big challenge. Among the efforts for sensing strategy, the liquid may take a positive participation. As discussed earlier, a high-density distribution of sensors is not necessary for rigid robots, whereas the complex motion of soft robots may really need plenty of monitoring points to acquire enough parameters. The number of sensors, which can be integrated in a single soft robot, is still far beyond that of animals, but a mobile sensory system coupled with liquid may make the best of a limited number of elements.
where the liquid mainly plays a role for transport. If available waterproof sensors are tiny enough, the inside sensor clusters will flow with the fluid. More importantly, the liquid itself can well reflect alternations. With the physical properties of deforming under shear stress, the flowing status may also reflect some traits of the motion, which would be captured as real-time information by specific sensors. The endolymph introduced earlier in Section 2.1.2 has actually proved the availability of liquid’s motion sensing function, which is fulfilled via inertial motions and the spatial arrangement of liquid chambers. An optimized flow structure of semicircular ducts can even help acquire more complex acceleration information. From a point of the chemical method, if containing some specific electrolytes or other functional solutes, the liquid can also respond to exact alternations via chemical effects. These changes can be captured as sensing signals. Details will be further discussed as the basis of a brand new liquid-involved intelligent system in the next section.

Such an idea is somewhat ahead of its time considering the current development of soft robots, for the flexible motion is still the very first challenge to consider. The realization of effective sensing synthesizes requests for advanced devices, strategy about signal capture and conversion, remote control, and so on.

Figure 5. Sensory systems of animals and manual facilities. a) The schematic of various receptors in the skin. Reproduced with permission. Copyright 2010, the Journal of Cell Biology by Rockefeller University Press. b) The structure of an optical curvature sensor. Reproduced with permission. Copyright 2013, Institute of Electrical and Electronics Engineers. c) A stretchable dual-capacitor multisensor for touch, curvature, strain, and pressure. Reproduced with permission. Copyright 2017, Springer Nature.
However, it is expected that visions along this direction can inspire more creations to overcome the barrier.

2.5. An Intelligence System with Liquid Participation

The earliest robotic intelligence mainly referred to an ability to work automatically under the guidance of predefined programming, which has been playing a crucial role in the automation of modern industry. Subsequently, a further intelligent request is dedicated to the autonomous controllable behavior such as humans. The artificial intelligence (AI) based on logic computation is an available strategy with the greatest progress at present. Humans have been imitating the mechanism of hominine neurons to innovate algorithms, such as deep neural network (DNN; Figure 6a), but the following demand for processing mass data has posed a huge challenge to the hardware. Nowadays, the manufacture technology of silicon-based semiconductor devices has seemingly hit a plateau, with the Moore’s law at a probable end. The inherent imperfection of the current framework about central processing unit (CPU) restrains its potential in parallel computing, which stems from the von Neumann bottleneck. These all largely raise the time and energy costs for such AI. Consequently, an optimization has been proposed to exploit new brain-like hardware, which is absolutely a more daunting undertaking.

For a typical AI system at present, the electrical signal is used to quantify changes in motion and deliver messages to processing unit, which is a fundamental feature of modern industrial intellectualization. This mode can be easily shared by rigid robots of electrical control systems, while it may not be available for soft robots. Influenced by novel actuating methods, the behavior of soft robots will distinctly feature random uncertainty; hence, the variations involved are quite difficult to be precisely quantified. These problems stemming from uncertainty would have to be handled via more complicated calculations, which will raise even more rigorous demands for hardware.

It can be easily observed that animals can use various substances to delicately regulate continuous variations of physical quantities, such as solution concentration and osmotic pressure, thus realizing the generation and transmission of information. A typical application is the delivery of nervous impulses, which is accomplished via Na⁺ transport across cell membranes and release and capture of neurotransmitters (Figure 6b). The biological information is actually established on these physical/chemical signals, which intuitively show variations of the entity, and then utilized by the nervous system. This is an utterly different intellectualized mode compared with humans via logic calculation. In addition, the fluids throughout the body can be found to make contributions in the generation and transmission of signals. The flexible deformation under shear actions enables liquid to respond to mechanical stimuli in different forms, such as flux, fluctuation, vortex, and so on. The dissolving capacity of liquid results in a highly adjustable solution system in composition, which further enriches the variability. Recently, some unique effects on specific liquids have been discovered, such as the smart response to concentration gradient[46] and diode such as the behavior of liquid metal (Figure 6c,d). All these characteristics may raise the liquid to a superior dimension where it can perform more diverse behaviors to reveal the received variations.

The mode of animals’ autonomous physiology may inspire us that one should imitate animals to establish a liquid environment as a high-fidelity medium of behavior information, where the liquid redefines the basic forms of signals in soft robots. Then, an intelligence system manipulating robots based on these intuitive variations may be developed. If possible, it can better deal with the uncertainty of soft robotic motion without complex signal acquisition and conversion via electron devices, and it will bring a thorough innovation of the AI mode.

The exploitation of liquid-based smart devices actually has a long history, where the liquid is used to represent signals, store information, and actuate mechanical computing devices. In the 1940s, a mercury delay line memory was invented by Eckert to serve computers as a storage at early ages. It mainly contained a long tube filled with mercury and piezoelectric quartz crystals at both ends of the tube.[50] The crystal converted serial data from electrical signals into acoustic waves, which traveled along the tube to another crystal, and external amplifying and timing circuits would assist to form a close loop[51] thus realizing the storage of information (Figure 6e). Such a device was successfully applied in those earliest stored-program computers, such as electronic delay storage automatic calculator (EDSAC) from England[52] and universal automatic computer (UNIVAC)[53] from America. Simultaneously, efforts were made to design and fabricate liquid-based logic devices in the late 1950s and the early 1960s, which directly relied on specific flowing phenomena, such as the laminar flow, the jet interaction, the wall attachment, and the vortex effect.[49] For instance, a liquid NAND gate was realized with two jet flows, where two nozzles are put in proper angles to ensure the confluence of flows (Figure 6f).[49,54] In addition, these logic devices were applied in the programmable sequence control, servo-control in marine applications, missile and aircraft control, etc. With the blossoming of semiconductor industry, these liquid-based devices gradually retreated from history in the 1970s, but they markedly demonstrated the abilities of liquid in the intelligence systems.

However, what cannot be ignored is that the manual manipulation of most physical/chemical signals is nowhere near natural creatures, and the matching control strategy is also a big challenge. As for the biochemically based intelligence, before one clearly figures out its mechanism, it cannot be enough to teach us a really biomimetic intelligence mode, which is an ultimate dream for smart robotics. Although quite difficult, the participation of liquid is a promising trial hoping to inspire innovations for components’ development in the future AI.

3. Potential Liquid Candidates for Making Future Soft Robots

After a particular interpretation about core roles the liquid may perform, attentions should be focused on another vital basic issue about which liquids can be qualified for these requests.

The biofluids of humans feature numerous categories, such as blood, lymph, gastric acid, sweat, and so on, every one of which has its own specific functionality with specific components. Therefore, the liquid, which may be qualified for the candidate, must meet some basic requests. With reference to the aforementioned sections, several obvious traits can be listed here, such as
Figure 6. Artificial and biological neuro network and liquid-involved intelligent behavior and devices. a) A typical pattern of DNN. b) The structure of a neuron. Reproduced under the terms of the Attribution 3.0 Unported (CC BY 3.0) license. Courtesy: Bruce Blaus, Wikimedia Commons. c) The experimental method and result of deformation induced by concentration gradients. Reproduced with permission. Copyright 2018, American Chemical Society. d) The experimental layout of liquid metal and the diode-like behavior. Reproduced with permission. Copyright 2017, John Wiley & Sons. e) The schematic of a mercury delay line memory. Copyright 2019, The Royal Society. f) The schematic of a liquid-based NAND gate. Reproduced with permission.
variability of flowing properties, affinity for functional additives, stability, and security for use. A more systematic conclusion still needs a lot of practice as essential accumulations in the near future. Even so, this article tries to recommend some potential choices at this stage.

3.1. Water as Intelligent Material

Water is the most common liquid. It seemingly has nothing unique, but this ordinariness does not hinder its participation in various robotic occasions. As an excellent solvent, the water can turn into various solutions with specific properties, which can be further used for chemical reactions, conducting microparticles, material modification. The smooth flowability of water enables it sensitive enough to deal with dynamic processes, which has been well acquired by humans and widely used in hydraulic machinery. Such a characteristic certainly has a potential to serve the hydraulic actuation of soft robots with suited apparatus. In addition, as the interacting mechanisms between water and many other substances are quite familiar to humans, it is more natural and convenient to conduct liquid-based trials with water. The stability of water is also a critical advantage for the durability of an application. Recently, the hydrogel applied for underwater soft actuators has aroused continuous interest (Figure 7a), where water plays a vital role in changes of the material. After all, the water is an unignorable candidate for its ubiquitous applications, which can easily meet the need for possibly numerous uses in terms of the expense, acquisition, and so on. It deserves more specific focuses.

3.2. Magnetorheological Fluid

Magnetorheological (MR) fluid is a smart material by dispersing quantities of microsized magnetizable particles into a nonmagnetic liquid environment, which possesses the capacity to let its rheological properties change rapidly when a magnetic field is applied. The MR effect is based on a field-induced magnetization of suspended particles, which attract each other in the direction of field lines and form catenulate aggregation, and consequently transforms the original low-viscous suspension to a more rigid state with a large yield stress (Figure 7b). The MR fluid, together with MR foam and MR elastomer, has become promising candidates in the mechanical field, such as vibration absorption and torque transmission.

The amazing characteristics of changeable stiffness enabled the MR fluid a novel alternative for the compliant leg design of rigid robotics. Current trials mainly tend to use the MR fluid-based damper in the walking structure, which can provide adjustable damping forces via changes of viscosity, thus regulating the compressing lengths or force conditions with the ground during the walk (Figure 7c). As with designs of soft robotics, although the bipedal or quadruped locomotion of animals is no longer the most necessary strategy to imitate, the variable stiffness structure is of positive potentials. The jamming effect, with an easy method to change the stiffness, has been widely used in various fields of variable stiffness devices, such as soft grippers, joints, pneumatic actuators, and soft manipulators. However, such devices are based on tiny granular materials with an inferior mobility, which must be constrained in finite space by specific membranes, so the jamming effect will prefer applications on some predetermined fixed positions of robots. With a similar functionality about stiffness adjustment, the MR fluid has a conversely superior flowing characteristic—thus it really has the potential to break new ground for soft robotics.

Besides the feasibility discussed earlier, details on applications should be equally emphasized as well. The performance of the MR fluid directly relies on magnetizable particles with requests of large saturation magnetization and small coercivity or remnant magnetization. The stability of the MR fluid is also a quite vital issue because of the complexity of two-phase dispersion. The tiny size of microparticles and the resulting large specific surface area are easy to induce problems of settling and aggregation of particles, respectively. The oxidation on the surface of particles poses a great threat to the durability of MR fluid because of abundant shed oxide skins. Efforts have been made to overcome these challenges, such as modifications of the particle surface or the solvent matrix. A series of novel magnetizable fibers have been discovered to own the potential to replace spherical particles with improved stability. Meanwhile, the function of the MR fluid requires an external controllable magnetic environment, which will refer to the design of magnetic circuits, the volume of field coils, stable high-power supply, and so on. The appropriate placement of these rigid components in a soft robot is obviously a big challenge. In addition, the available operation mode in soft robotics is of urgent needs, which refers to the transformation of materials and the structure of gathered particles. All current applications of MR fluid are mainly based on the following: 1) valve mode; 2) direct shear mode; 3) squeeze mode; or 4) a combination of these three (Figure 7d). However, whether they can be directly applied in soft machines remains to be evaluated. It is possible that new modes are required for the breakthrough actuation method on soft robots.

3.3. Liquid Metal

The liquid metal refers to a series of pure metals or alloys, which feature low melting points around room temperature, high surface tension, flexible deformability, great thermal and electrical conductivities, low toxicity, and some other fascinating characteristics. Applications based on liquid metals have been vastly broadened, including advanced thermal management, soft electronics, biomedical equipment, and so on. However, humans have further expectations for liquid metals. The T-1000 robot in the famous movie Terminator has greatly enriched the imagination of unborn advanced robots in the future, which was made of highly intelligent deformable liquid metal materials and showed extremely great features as a soft robot with the nearly ultimate form. With the emergence of modern soft robotics, a desire for the performance of the liquid metal in such fields is emphasized.

The flowability of liquid metal is superior than the water with the kinematic viscosity value of $2.5 \times 10^{-7} \approx 7.5 \times 10^{-7}$ $\text{m}^2\text{s}^{-1}$. Such a good mobility enables the liquid metal to be easily injected into narrow cavities or slender tubes and flow smoothly, which is a key premise if the liquid is
Figure 7. Potential liquid candidates. a) A hydraulic hydrogel actuator working in aqueous solutions. Reproduced with permission. Copyright 2017, Springer Nature. b) The microstructural changes of the MR fluid under an external magnetic field. Reproduced with permission. Copyright 2010, Royal Society of Chemistry. c) Side view of an MR fluid-based variable stiffness leg structure. Reproduced with permission. Copyright 2019, Elsevier. d) Basic operation modes of MR fluid. Copyright 2000, Elsevier. e) Schematic diagram of a four-wheel liquid metal robot, which is inspired by an electric field. Reproduced with permission. Copyright 2019, Elsevier. f) Another design of a wheeled robot actuated by altering the robot’s center of gravity based on a liquid metal droplet. Reproduced with permission. Copyright 2015, John Wiley & Sons. g) Self-fueled liquid metal motion pattern via feeding style. Reproduced with permission. Copyright 2015, John Wiley & Sons. h) The possible applications of ionic liquids. i) The function principle of the ILG soft actuators. Reproduced with permission. Copyright 2019, Hindawi.
supposed to participate in regulating the dynamic balance. However, the uniqueness of liquid metals mainly lies in the more active role for actuating soft machines. The deformation and locomotion under coupling of electrical field and chemical effect are the most miraculous characteristics of liquid metals. These diverse properties have constructed a storage of original ideas, which may inspire several novel prototypes about soft robotic actuators. For example, the motion of liquid metal droplets in alkaline solutions under an electric field has been successfully applied as a motor to actuate small robots (Figure 7e,f). Various deformation effects based on surface tension changes, such as self-trigged vibration, amoeba-like deformation, photochemically induced motion, and graphite-induced periodical self-actuation, are all have the potentials for robotic application. Energy supply is another vital issue where the liquid metal still shows unusual properties as well. A bulk liquid metal with aluminum swallowed can behave like a synthetic self-fueled motor in solutions, spontaneously experiencing a transformation from chemical energy to kinetic energy. The mechanism involved refers to an electrochemical energy production (Figure 7g). Besides propelling the metal pneumatically, the hydrogen itself is an ideal fuel undoubtedly. Previous trials about soft robots have verified the feasibility of actuation by combustion and chemically gas production, both of which are applicable for hydrogels. Moreover, the liquid metal-based hydrogen production is much easier to operate with few requests about reactive conditions and reactant preparations, so it is really as close to biochemical energy supply mode as possible. The softness control on liquid metal usually results from the optimization for inks in printed electronics, and relative strategies can also be used for the soft robotic application. In addition, some novel innovations, such as liquid metal enabled droplet circuits, which can function in solutions, may eventually contribute to intelligence style where the liquid participates as visualized earlier.

However, gaps still exist between promising potentials and expected applications. The fact that most deformation and locomotion effects of liquid metals are only available in aqueous environments has somewhat posed an obstacle to applications for more occasions. A proper settlement for solutions in the structure is a key challenge. The dosage of liquid metal used in experiments is still small. Therefore, these effects may be available for pony-sized robots, but those designs with normal sizes will call for kinematic effects in vast scales, which means a manipulation of rather larger amounts of liquid metals. In a nutshell, characteristics discovered so far about the liquid metal have enabled it promising applications for soft robots in some specialized occasions, such as microscale space and underwater task. As for the imaginary amazing liquid metal soft robot, such as the T-1000, more work is needed.

### 3.4. Ionic Liquid

The ionic liquid is a special kind of organic salt with its melting point near room temperature. Compared with the classical inorganic salt solution, which features an aqueous solvent of numerous electrically neutral molecules, the ionic liquid is composed entirely of ions that inherently influence its characteristics.

| Component | Organic cations (pyrrolidinium, imidazolium, sulfonium, etc.); Organic or inorganic anions ([OTf]−, [BF4]−, [SbF6]3−, etc.) |
|-----------|----------------------------------------------------------------------------------------------------------------------------------|
| Melting point | Mostly below 100°C |
| Thermal stability | Favorable |
| Surface tension | Moderate |
| Vapor pressure | Negligible |
| Polarity | Moderate |
| Conductivity | <10−2 S cm−1 near room temperature; increasing with higher temperatures |

Table 1 represents some attractive properties of ionic liquids that can lead to various applications. For example, the nonvolatility, thermal stability, and favorable solvating power enable it to form an excellent green solvent for synthesis and catalysis to substitute volatile organic compounds (VOCs), most of which are environmentally harmful. The conductive characteristic declares its potential in electrodes, fuel cells, solar cells, and other electronic devices. When mixed with proper ionic gels of the polymer matrix, it can transform into a solid composite (ionic liquid gel [ILG]) with a cross-linked 3D network and function in solid states for special occasions, such as separation and thin-film transistors (TFTs). In addition, diverse combinations of proper cations and anions can be achieved to synthesize different ionic liquids (nearly 1018 kinds in theory), thus enabling designable functionalities. Undoubtedly, the ionic liquid will be a booming area of multifunctional materials with various applications (Figure 7h).

Besides current applications on hot topics of the ionic liquid, it virtually has a big potential in the field of soft robots as well. As mentioned earlier, the current development of soft robots deeply relies on the breakthrough of smart materials, for which the function-designable property of ionic liquids is exactly qualified. For instance, the ionic electroactive polymer (IEAP) is a popular intelligent material applied for soft robots, which can perform large deformation via electric excitation transport of inner ion or solvent. IEAP soft robots actually face challenges of rather larger amounts of liquid metals. In a nutshell, characteristics discovered so far about the liquid metal have enabled it promising applications for soft robots in some specialized occasions, such as microscale space and underwater task. As for the imaginary amazing liquid metal soft robot, such as the T-1000, more work is needed.

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directly in the liquid state. The body fluid of animals is inherently a complex electrolyte solution system containing various organic and inorganic particles with immeasurable quantity ratios, presenting a dynamically stable and efficient status. It offers excellent environments and adequate reactants supplies for most biochemical processes, which mainly serve the physiological activities. Therefore, for an organic natural life, a functional electrolyte solution system is the indispensable guarantee for its biochemically based physical activities. The biomimetic soft robot in the future will feature an inner liquid system as we imagine, and some critical activities of the robot, such as energy supply, would be relied on reactions in the liquid phase just like biochemical processes, so this liquid system must assume essential chemical functionalities. Subsequently, the ionic liquid is a promising candidate. First, it owns excellent stability compared with most organic solvents. Second, the characteristic of good solubleness for both inorganic and organic substances can enrich the variety of functional particles in the liquid system, similar to that of the body fluid. Third, it can offer various cations and anions for targeted applications based on the function-designable property. Therefore, the ionic liquid can be a good choice for a functional stable chemical liquid system, as a universal carrier of electrolytes and proper liquid environment.

So far, new applications about the ionic liquid are continuously emerging, and it certainly owns talents in the field of soft robots. The optimization to IEAPs with ionic liquids is an available strategy considering current requirements for more advanced soft robotic materials. Meanwhile, the potential of ionic liquids as an excellent electrolyte environment should be noticed as well. In the future, it will pave a way to various chemical functions of the robotic liquid system.

4. Challenges in Theoretical and Technological Issues to Develop I-LIFE

After a conjecture about potentials of the I-LIFE for soft robotics and an enumeration of possibly available types of functional liquids, we can never ignore the huge gaps laid ahead of these optimistic expectations. As a novel conception, this envisaged system with probable participations in motion, energy, stiffness adjustment, sensing, and intelligence does not achieve any prototype verifications yet. Nevertheless, if the liquid entity is included into a soft robot, it must function as a complete subsystem referring to driving sources, circulatory routes, functional fluids, flow monitoring, interaction channels, chemical reaction species, and so on, where some fundamental challenges can be concluded as below and inevitable for further development.

4.1. Controllable Flow in Complex Pipe Networks

As mentioned earlier, the potentials of liquid in soft robotics are largely built on its flowing characteristic, so realizing a controllable pipe flow in the whole structure like blood in vessels is a basic request. The attainment of such a network primarily demands a deep understanding of fluid dynamics in pipes, whereas technique difficulties cannot be ignored as well.

4.1.1. Theoretical Challenges

The description of incompressible flowing generally depends on the governing Navier–Stokes Equations, that is

\[
\rho \frac{\partial \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \mu \left( \nabla \mathbf{v} + \nabla \mathbf{v}^T \right) + \mathbf{F}, \quad i = 1, 2, 3 \quad (1)
\]

where the unknown variables \( p \) and \( \mathbf{v} \) are needed to predict flowing situations in a given condition. To describe the distribution of pressure and flows in pipes for engineering needs, the driving pressure, hydraulic loss, flow rate, and hydraulic diameter are specific required parameters, which can be handled via simplified flow models. If a Newtonian fluid is considered a steady horizontal laminar flow with no entrance effects, a common Hagen–Poiseuille Equation can be adopted to determine the relationship between flow rate \( Q \) and driving pressure \( \Delta p \) (flow resistance as well).

\[
\Delta P = \frac{8 \mu L Q}{\pi r^4} \quad (2)
\]

Such a solution was first proposed in hemodynamics to understand the blood flow, and it is appropriate for the conditions that the flow length is substantially longer than its diameter. Similarly, the calculation of local resistance can be done by Equation (3).

\[
\Delta P = \frac{\zeta \rho v^2}{2} \quad (3)
\]

where \( \zeta \) is the local friction coefficient determined via experiments.

However, these typical formulas are not enough to solve the problem yet. A quite significant uncertainty is the softness of pipes. It is easy to imagine that the pipe network in soft robotics must feature a characteristic of enough elasticity to accommodate the large-scale deformation and motion. Therefore, the pipe walls are prone to markedly interact with fluids, thus leading to an actually labile flow state. Such a fluid–solid coupling interaction mechanism has penetrated the category of rheology, making the real situation more complicated. In addition, the network is a branching structure with different diameters, so flow through branch points will conduct intricate distributions of velocities and wall shear stresses, with possible swirling. In brief, either the rheological behavior or the perturbation triggered by the complex network can alter the real behavior far beyond the laminar steady flow assumption, gradually increasing the difficulty in parameter designs.

4.1.2. Technological Barriers

Assuming that all parameters can be confirmed satisfactorily, problems resulting from technology cannot be underestimated. A pump may easily afford the whole energy demands, but the flow regulation between artery and branch pipes is much more difficult, which acquires local fine energy input. The vascular smooth muscle cells in animals are discovered essential to regulate blood flow, whereas artificial elastic pipes are incompetent.
so far. A combination of micropumps, microvalves, and flowmeters may be an alternative in terms of current technology. As for some other unfavorable risks, they are likely to appear in the occurrence of cavitation, the durability of pipe materials, the degeneration of fluids, airtightness of pipes, responsiveness of control elements, and so on, every one of which is associated with the operations of the system. In short, not only the establishment but also the maintenance of such a flow network is a huge project.

4.2. Effective Interaction between Liquid and Functional Body

Besides the potentials exhibiting based on flow characteristics, the liquid can also function via interaction with specific objects, which is mainly reflected in stiffness alternation and liquid-based fueling reactions. In general, such a hypothesis is originally inspired by the delicate biological structure, such as cells, for they can easily adjust some of their properties by directly interacting with the surrounding liquid environments. Consequently, the functional material itself is the primary challenge underneath the idea of liquid-inducing stiffness alternation. It should have necessary affinity to given liquids and be expansive with quick response, whereas the strength needs to bear stresses in a frequent cycle deformation. More importantly, the liquid absorption and liquid loss should be triggered via controllable stimulus; otherwise, the reversibility cannot be ensured. The development of soft robotics exactly coincides with the emergence of more advanced soft materials, which is amply demonstrated as mentioned earlier.

Simultaneously, the assistant role of liquid still raises several technological claims. For example, the liquid should have good contacts with the functional body, so the shape design and placement of vessels need careful consideration. When the liquid is participated in fueling reactions, its contact with another solid reactant directly decides the occurrence and termination and rate of energy supply, so the controllability should be taken seriously. In addition, the internal characteristics of liquid will obviously influence the interaction as well. Overall, a continuous and controllable contact guarantees the subsequent interaction between liquid and other materials and reactants, which is supposed to be an essential attention.

5. Conclusion

Human’s fascination with robots has extended millennia. The long-term accumulations of technology, such as machinery manufacturing and electrical control, all accelerate the blooming of rigid robots, which, in turn, greatly fulfill the demand for various specialized working occasions. However, what humans ultimately pursue is far more than a specific cold mechanized facility, but a versatile humanoid entity.

The emergence of intelligent soft robots blazes a promising path to bridge the aptly gaps between artificially complicated structures and natural flexible organisms, for it is so far the trial that may furthest approach the biological characteristics. Although there are novel prototypes springing up constantly, the current endeavors dedicated to soft robots are somewhat scattered. Therefore, they need unifying under an explicit banner. Based on elastic materials and deformable structures, the soft robotics must be supported by its exclusive methods rather than mere modifications on the rigid category. Establishing a new guidance theory is an extremely challenging feat, but inspirations can be obtained from nature. In bionics, humans have chronically laid focuses on those exquisite topology structures, while what nature can enlighten is far beyond this, so new attentions could be put where it has been ignored for a long time. After all, nothing pivotal has been thoroughly affirmed as basic referring principles in the field of soft robots, and innovations should be developed in a much bolder way.

Raising these thoughts about liquid is not an abuse of bionics, but a desire to call for more brave thoughts enriching strategies for developing advanced soft robotic design. Almost every creature features an inside fluid environment to conduct numerous known and unknown physiological functions, but it is usually overlooked due to its incompatibility with the pre-existing man-made equipment and some other engineering inconveniences. For maturely systematic rigid machines, the technical subversion triggered by liquid is possibly unnecessary, but biomimetic soft robots may really take advantage of it. The I-LIFE as raised in this article perhaps reminds human’s wishful vision of future advancement whose superiority is bountiful and stretches across many disciplines. Meanwhile, theoretical and technical challenges should be taken seriously as well. At the hopeful beginning of soft robotic development, the emergence of various potential ideas may eventually enrich the knowledge of this new land.

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Conflict of Interest

The authors declare no conflict of interest.

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biomimetic robotics, Intelligent Liquid Integrated Functional Entity (I-LIFE), intelligent liquids, smart machines, soft systems

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