

# Soft Bionic Sensors and Actuators

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Nature is an unlimited source of inspiration for soft bionic sensors and actuators, which have been recently spotlighted for applications in soft robotics. Soft bionic sensors are sensing platforms that can bend, stretch, or morph shapes to allow for the detection of external stimuli such as force, displacement, pressure, temperature, or chemicals under slight mechanical deformations. Soft robotics technologies have now evolved beyond tactile sensing, and devices with displacement, temperature, or light detection capabilities are currently under development. Owing to advances in the field of conductive composite materials, various types of soft bionic sensors have been introduced, such as flexible, stretchable, and wearable sensors. With respect to soft bionic actuators, early developments on dielectric elastomers have led to the recent realization of artificial muscles based on smart polymer materials. While pneumatic actuators have opened the field of soft robotics, recent developments include various soft and smart actuating mechanisms using fluids, chemicals, and soft materials. Also, novel manufacturing technologies, such as 3D printing, have been ushering the advancement of soft bionic actuators for soft robotic fingers inspired by biomimetic structures such as insects, or adopted by architected solids like auxetic or origami structures. Owing to the increased interest in flexible soft robotics, which is expected to offer alternative ways to build soft and diverse robots, soft bionic sensors are anticipated to consistently grow in importance and become industrially relevant.

Before considering the creation of novel soft bionic sensors and actuators, it is highly recommended to consult other fields such as material science to consider existing knowledge on soft and smart concepts. Thus, one of the challenges in soft bionic sensors and actuators is the interdisciplinary collaboration among other engineering fields. To showcase recent advances in this rapidly growing field, we have organized this special issue of *Advanced Intelligent Systems* focusing on “Soft Bionic Sensors

and Actuators”. It is intended to make an open discussion for ongoing interdisciplinary research from various fields and to provide an outline for potential applications. The issue brings contributions together from experts and covers the following three key aspects of soft bionic sensors and actuators:

## 1. Novel Material Technologies with Design and Development for Soft Bionic Actuators

Michael D. Dickey, Tae-il Kim, and co-workers (article number **2000159**) reviewed gallium-based liquid metals for the biomedical sensors and soft actuators, which are representative stretchable conductors with metallic conductivity and nearly unlimited extensibility due to their liquid nature. Despite their enormous surface tension, liquid metals can be patterned into non-spherical shapes, such as wires, due to the presence of a native oxide shell. The thin oxide layer also enables the formation of stable liquid colloids and micro/nanosized droplets that do not coalesce so easily. The oxide layer can be exfoliated and chemically modified into semiconductor 2D materials to create and deposit atomically thin materials at room temperature. This review summarizes physical and chemical methods of modifying the surface of liquid metal to tune its properties. The surface modification of liquid metal provides unique applications, including use in soft biomedical sensors and actuators with mechanical properties similar to human tissue.

Hyun-Joong Chung and co-workers (article number **2000186**) reviewed magnetically controlled soft robotics utilizing elastomers and gels in actuation. A magnetic field has unique advantages in controlling soft robotics inside of an enclosed space, such as surgical catheters or untethered drug-delivering robots operating in the human body. Soft actuators, made of elastomers and gels functionalized with magnetically active materials, are a natural choice to drive magnetically controlled motions of the soft robots. Recent innovations in soft material technologies, including 3D printing, origami/kirigami, tough hydrogels, mechanical metamaterials, and liquid metal injected elastomers, offer technological foundations to develop soft actuators and robots with significantly enhanced performance. This review provides an overview of magnetic soft actuators and robots from a materials engineer's perspective. In this review, the applications of the magnetically-controlled soft robotics in surgical and therapeutic medical devices are discussed.

## 2. Novel Wearables Using Soft Bionic Sensors

Jamie Paik and co-workers (article number **2000168**) developed a novel wearable haptic feedback device. While there have been continuous efforts to recreate these haptic experiences for applications in rehabilitation, or medical and educational tools using

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master/slave control, haptic devices are still limited in invoking intricate and rich sensations. This paper presents the design, model, and experimental validation of a wearable skin-like interface able to recreate the roughness, shape, and size of a perceived object; a platform for an immersive physical experience. They demonstrated for the first time how artificially created tactile feedback can indeed simulate physical interaction such as surface roughness, dimension, and shape, transferring a virtual experience effectively into a physical one.

Ravinder Dahiya and co-workers (article number **1900145**) demonstrated a novel tactile sensing device (SensAct) with soft pressure sensor seamlessly integrated as an integrated flexible actuator. The soft sensor was embedded in a custom 3D-printed fingertip of a prosthetic/robotic hand to demonstrate its use for pressure mapping along with remote vibrotactile stimulation using SensAct device. The self-controllable actuation of SensAct could provide eSkin the ability to tune its stiffness, while the vibration states could be utilized for controlled haptic feedback.

### 3. Emerging Applications of Soft Bionic Sensors and Actuators

Soft robots have been considered to have infinite degrees of freedom based on their structural compliance, providing high adaptability to the environments, and recent study has focused mostly on their physical designs for increasing the adaptability. Yong-Lae Park and co-workers (article number **2000061**) demonstrated hybrid system analysis and control of a soft robotic gripper. They consider a soft robotic system as a hybrid system described by both discrete and continuous states and propose a method of analysis for enhanced manipulation performance. Therefore, they first determined the optimum location of sensor embedment on the actuator based on the calibration map obtained from actuator characterization, and developed a control strategy for the gripper to find the best position to grip the object based on the estimated states.

For human-robot collaboration, the exterior material of robot body is required to have the ability to sense the external environment, and needs to possess the function of cushioning the collision between human and robot. Geng Yang and co-workers (article number **2000038**) demonstrated fluid-driven soft CoboSkin for safer human-robot collaboration. In this article, a fluid-driven soft robot skin with sensing and actuating functions is applied to a collaborative robot and working well with the host robot. By altering the internal air pressure in pneumatic actuators, the developed robot skin can provide more than ten times higher tunable stiffness and sensitivity. The 3D printed skin is attached to a collaborative robot conformally. The CoboSkin provides the robot with multi-functions, which are similar to those of human muscles and skin attached to human bones. By mimicking human skin and muscle's tactile sensing

and stiffness tuning functions, CoboSkin demonstrated better human-robot interaction in our daily activities.

Continuous monitoring of vital signs can be a life-saving matter for different patient groups. Matti Mäntysalo and co-workers (article number **2000030**) developed an unobtrusive, low-cost measurement and monitoring system for out-of-hospital and in-hospital applications. More intelligent and unobtrusive systems are currently being developed in order to improve the usability of body-worn monitoring devices. Body-worn devices can be skin-conformable, patch-type monitoring systems that are comfortable to use even for prolonged periods. In this study, they propose an intelligent and wearable, out-of-hospital, and in-hospital 4-electrode electrocardiography (ECG) and respiration measurement and monitoring system. The system consists of a conformable screen-printed disposable patch, a measurement unit, a gateway unit, and cloud-based analysis tools with reconfigurable signal processing pipelines. The performance of the ECG patch and the measurement unit was tested with cardiac patients and compared with a Holter monitoring device and discrete, single-site electrodes.

Tse Nga Ng and co-workers (article number **2000106**) developed artifacts mitigation in sensors for spasticity assessment. Spasticity is a pathological condition that can occur in people with neuromuscular disorders. This paper presents an instrumented bi-modal glove with force and movement sensors for spasticity assessment. The motorized robotic arm system offers adjustable resistance to simulate different levels of muscle stiffness in spasticity, and the sensors on the robot provide ground-truth measurements of angular displacement and force applied during flexion and extension maneuvers. The robotic sensor measurements are used to train the instrumented glove data through multi-task learning. After processing through the neural network, the Pearson correlation coefficients between the processed signals and the ground truth are above 0.92, demonstrating successful signal calibration and noise mitigation.

We hope that this special issue focusing on soft bionic sensors and actuators will bring knowledge, insight, and inspiration to readers. The research in this area is highly interdisciplinary and combines expertise from several fields, such as materials science, physics, mechanical engineering, electrical engineering, biomedical engineering, etc. We look forward to the accelerated growth of development efforts in this field which would lead to expansive possibilities for technological translation to relevant fields.

To close, we are indebted to all the authors with their insights on this exciting and explorative area of soft bionic sensors and actuators for the contribution to this Special Issue. Moreover, we are thankful to the editorial team of *Advanced Intelligent Systems* for their support and their willingness to experiment, in particular Dr. Floriano Cuccureddu and Dr. Babak Mostaghaci.



**Woo Soo Kim** began his career at Xerox Corporation after postdoctoral work at MIT. Since he came to Simon Fraser University BC Canada in 2010, he had been developing advanced materials for 3D printing, contributing to biomedical wearables and sensing robot systems. His research finds solutions to engineering challenges for health, energy, and technology sectors. Recently, his research is focused on the advanced 3D printing technologies for architected solids and 3D printed sensing robot applications.



**Jamie Paik** is the director and founder of Reconfigurable Robotics Lab (RRL) of the Swiss Federal Institute of Technology (EPFL). RRL's research leverages expertise in multi-material fabrication and smart material actuation toward unique robotic platforms. At Harvard University's Microrobotics Laboratory, she started developing unconventional robots that push the physical limits of material and mechanisms. RRL's self-morphing Robogamis (robotic origami) and soft robots continue to evolve and demonstrate their direct applications in medical, automobile, space, and wearable robots.