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Guest Editorial

Soft Medical Robots-Revamping the Diagnostics and Therapeutics Technologies

Introduction

Imagine, a large, benignant, soft and huggable, humanoid robot by your side caring for you, with the know-how of many medical procedures and has a barely evident fiber skeleton yet makes no big deal about it. Does it ring a bell? Well yes, it is Disney's Baymax from Big Hero 6. Such an exceptional human–robot interaction is not just a fiction; it is a likely state of affairs and the current trend. In fact, an inflatable Baymax draws its inspiration from decades-long and current research on soft robotics at Carnegie Mellon University in the healthcare field [1]. Like an magnetic resonance imaging (MRI), which is basically designed for atomic structure studies and later used in medical imaging, the soft robotic actuators are also initially developed outside the clinical research realm and later found their way into the medical device innovations.

Soft robotics is the introduction of nonconventional actuating materials with low Young's modulus or deformability, such as polydimethylsiloxane (PDMS), shape memory alloys, shape memory polymer, and electro-active polymers to acquire large-scale deformation of the whole robotic structures with the vision to impose biomimetic behavior in them [2–5]. The compliance and the elasticity of soft body parts in a robot allow unsupervised reactions with interaction forces and support the bio-inspired locomotion such as morphing, squeezing, flipping, climbing, growing, and crawling that would not be possible with an approach based only on rigid links [4,6–9].

As per World Health Organization, medical device innovation refers not only to the invention of new devices but also to adjustments to, or incremental improvements of, existing devices and clinical practices [10]. That is precisely how soft robotic actuators and technologies are contributory in translational research as well as innovation in diagnostics and therapeutics devices. Soft materials, with their compliance, allow conformity and innocuous cooperation with the human body. Therefore, medical practices requiring device–body interaction have a hastily growing bias for this soft-touch campaign. In this editorial, we are discussing the recent soft robotics developments and technologies in designing the medical devices.

Soft Robotic Devices for Cardiac Therapeutics

A host of designs in cardiac devices are focusing on the use of soft actuators in developing devices for functional cardiac support as well as high fidelity heart models for research and training [3,11–15]. A patient-specific compliant direct cardiac compression device developed by Mac Murray and his group use compressed air to inflate elastomer foam chambers and applies compression to the exterior of a heart [11]. This direct cardiac compression is one of its kind as it accounts for the variations in patient-to-patient heart geometry and applies compression without adversely squeezing the coronary arteries. Similar in function, ventricular assistive devices (VAD), means to bridge the gap of transplantation to recovery phase, are also evolving with soft robotics [12–14]. A novel VAD surpasses the need of any triggering mechanism for synchronizing with natural rhythm while augmenting the cardiac function, thanks to its real-time sensing of hemodynamics and automated control [12]. This modular McKibben actuator-based extra-cardial septal bracing incorporates a series of functionalities to promote diastolic function and temporal synchronization with the native heart. An intraventricular balloon pump VAD assistance utilizes the systemic inflation and deflation of a polyurethane membrane to achieve its functionalities [14]. A biorobotic hybrid heart composed of organic endocardial tissues and soft robotic myocardial band has a superior dependability in representing the cardiac motions and endocardial anatomy as compared to the existing in vivo porcine and in-silico heart models devices for intracardiac studies [15].

Soft Robotic Devices for Surgeries

The innovation in surgical devices is having steep transients in its dynamics with the introduction of the soft robotic actuators, especially in minimally invasive surgery (MIS) [16–21]. The STIFF FLOP projects addresses many intrinsic difficulties, such as lack of dexterity and internal triangulation in MIS procedures [17–19]. A soft robotic optic arm with tunable stiffness achieved superior angles of vision of the surgical field in the pelvis for the total mesorectal excision [17]. The ferromagnetic anchors and soft central retractor bag with ground coffee with a global application of target tissue retraction is an unprecedented development in MIS. Magnetically anchored soft robot tunes its stiffness for specific abdominal organs retraction such as liver, stomach, and intestine [18]. A soft modular pneumatic robot with jamming characteristics in series with rigid robot arm qualifies electrical diathermy cutting to lower its intra-operative risk index [19].

Other than mechanical tuning, the use of magnetically navigable and vacuum-powered laparo-endoscopic single-site soft robots are also increasing [20,21]. A soft magnetic anchored and guidance system with visual control provides video assistance during thoracic surgery that lessens the intricacies in tracking the surgical instrument owing to site crowding [20]. The novel bio-inspired vacuum suckers on the surface of the kidney provides an accurate track-guiding for the pre-operative ultrasound imaging in nephrectomy and thus evading the challenges of organ repositioning and organ slippage. The purported advances are reaped in natural orifice transluminal endoscopic surgery (NOTES) too [22,23]. A soft Sarrus-linkage capsule NOTES robot, is magnetically actuated for fine-needle biopsy in gastrointestinal track, has a precise needle control and improves the diagnostic accuracy of submucosal diseases and tumors [23].

Soft Robotic Devices for Vascular and Nerve Pathologies

Human body vasculature is like a doodle art that intersperses the whole body and navigating through such miniscule tubes is perplexing. The fiber-reinforced enclosed elastomers and magnetically steered microsoft robots are hence game-changers in intravascular treatments [24–26]. The deformation model of the soft microrobot under magnetic actuation is steering submillimeter-diameter guidewires through a 3D phantom coronary artery in the event of coagulation [25]. Another submillimeter-scale soft robot with new-generation materials succeeded in steerable laser delivery in in vitro environments relevant to the clinical challenges of intracranial aneurysm. This self-lubricating soft continuum robot with omnidirectional steering owes its navigating capabilities to ferromagnetic domains programed in its soft body while growing hydrogel skin on its surface for lubrication [26]. During nerve laceration, surgeons can minimize the unintended iatrogenic nerve trauma while performing the digital nerve repair surgery with stiffness tunable soft grippers [27].

Soft Robotic Devices for Drug Delivery

In situ drug delivery or cell injection is a never diminishing field of exploration interests since 1928, when Nobelist Werner Forssmann performed the first cardiac catheterization on himself [10]. A new magnetically driven microrobots, composed of alginate-hydrogel mix with magnetic nanoparticles have been used as tumor drug carriers. These robots swell and deswell in response to temperature changes caused by external near-infrared stimuli performing therapeutic cell delivery at the targeted sites [28]. Similarly, a milliscale dynamic soft reservoir is a versatile tool, when selectively actuated, modulates the biomechanics of foreign body responses at locations of in-dwelling medical devices and thus ameliorate their life-span [29]. The microcell injection experiments on crab eggs conducted with piezoresistive force sensor embedded in soft-flexure mechanism reported an improved success rate and survival rate of cells [30]. The tactile sensing can unlock a new level to the efficiency of the whole practice, by enhancing precision, control, and safety which is verified with custom-made flexible piezoresistive materials or star shaped magnetic grippers, wrapped with a biocompatible hydrogel polymer [31,32].

Soft Robotic Simulators and Organ Phantoms

Many computational biosimulator models are more than usually idealistic and fail to validate, especially in the replication of the mechanical characteristics of the muscles or vasculature which varies with age and pathophysiological state. Soft robotic in vitro simulators are hence developed as supplementary approach to in vivo studies of pathophysiological stages. A unique soft robotic phantom that simulates the cervix softening through the loading of a Foley catheter-like mechanism is used in training of midwifery and obstetrics students [33]. The researchers have developed a host of radially actuating designs shaping into biomimicking swallowing and digestive organs [34–36]. The esophageal robot is a providing an in vitro analyzing tool for food texture modification in dysphagia management [37].

Soft material tissues or organ phantoms have already been used in medical practices widely to reproduce surgical sites or training tissue handling devices [38,39]. The EndoAbS project is an effort to enrich open source datasets of endoscopic stereo images with 3D phantom soft abdominal organs made of bicomponent polyurethane elastomer with varied stiffness [40].

Soft Robotic Devices for Prosthetics and Rehabilitation

Joseph L. McKibben devised the biologically inspired pneumatic artificial muscles in the 1950s when he developed arm orthotics for his daughter. The idea was later commercialized in the 1980s under the name of rubbertuators [41]. Many research groups are dedicated to provide novel soft actuator designs and integrated solutions for limb rehabilitation and prosthetics [42–44]. A lightweight and stretchy exosuit for assisting elderly and rehabilitating patients with movement disorders due to Parkinson's disease or stroke, etc., has a seamless integration of robot with human using soft actuators. This suit is adaptable and have personalized control strategies thereby improves the patient's balance, strength, and endurance [45]. A novel prosthetic solution to brachial plexus injury is soft robotic, fabric-based pneumatic assistive gloves, which can provide simultaneous assist with the thumb abduction and finger flexion and extension motions in grasping [46].

Soft Robotic Devices for Dental Applications

Soft robotic researchers are also paying attention to the mounting and unmet needs of dental health care. The soft bracing machine is a soft robotic adaptation of the conventional bulky bracing machines used in orthodontics with the superpowers of compactness, tendon-sheath transmission, smaller footprint, and cost-effectiveness [47]. Hwang et al. devised a catalytic antimicrobial robot that pulls over at the biofilms on the surfaces in the interior of human teeth and drives away the biomass with it. These magnetically driven "kill-degrade-and-remove" biohybrid catalytic antimicrobial robots could mitigate biofouling of medical devices and diverse confined anatomical surfaces [48].

Future Prospects

The advent of soft medical robotics has undoubtedly revamped the therapeutic practices and also exposed those forgotten; however, the most necessitated demands of diagnostics, like proprioception of catheters, in situ muscle-mimetic actuations, modularization of solutions for global applications, and in situ sensing of prosthetics. Though at their infancy, some of the recent works are engaged at delivering pragmatic solutions to these needs [49,50]. The Peano-HASEL actuators provide linear and perhaps precisely controlled muscle actuation for grasping [51] and the soft-ring actuator mimics the circular muscle actuation, thus paving the way for developing organs with muscular radial occlusion [52]. Omniskins are robotic skins when attached at different orientations designate different functionalities to the robot actuators and hence are a suitable modularization for gait exosuits [53]. Furthermore, earthworm inspired both proprioceptive robot [54] and the modular robot [55] are also awaited for their fully functional debut in MIS. The researchers are deploying artificial intelligence and deep learning in learning the soft robot in situ interactions and reporting to human–machine interfaces [56,57].

Challenges to Practitioners and Innovators

Even though soft robotics have a prolific impact on the medical practices, there does not exist a quantified or qualified measure of the degree of softness required or permitted. Softness can be intended in various ways: soft texture, soft and deformable materials, soft movement, use of elastic materials and variable compliance actuators, and soft in friendly and natural interactions with people. The measures to initiate the development of a soft robotic ontology is challenged by these varieties, and seemingly unprecedented forms of robots emerging. Also, the learning curves define the rate of progress in gaining new skills or experiences, especially in surgery. Therefore, measures are to be initiated to assess the learning curve patterns for soft robot-assisted surgical procedures. It is highly recommended as these curves can have considerable impact on surgical metrics, cost advantageous decisions, and clinical outcomes. A collective and constructive agreement between the innovators and the practitioners are henceforth essential to reap the benefits and mold the next-generation medical devices.

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