COMMENT

Human-in-the-loop development of soft wearable robots

Conor Walsh

The field of soft wearable robotics offers the opportunity to wear robots like clothes to assist the movement of specific body parts or to endow the body with functionalities. Collaborative efforts of materials, apparel and robotics science have already led to the development of wearable technologies for physical therapy. Optimizing the human–robot system by human-in-the-loop approaches will pave the way for personalized soft wearable robots for a variety of applications.

It is exciting to imagine a future in which soft wearable robots can be worn underneath clothing. This would enable a paradigm change in how we assist healthy individuals (for example, by providing support to soldiers overburdened by heavy loads) and patients with mobility impairments (for example, by eliminating the need for canes, plastic braces and walkers). A rapidly increasing number of academic and industry groups are working on the development of soft robotic component technologies and integrated soft wearable robot systems. Soft wearable robots will not replace traditional rigid exoskeletons that are emerging as a valuable clinical tool for patients with severe impairments, but will instead offer complementary capabilities for applications which require soft systems.

The Ironman suit

Over the last two decades, a variety of rigid exoskeletons have been developed for tasks ranging from heavy lifting to walking assistance. Rigid exoskeletons rely on inelastic frameworks of linkages, coupled to the body at specific locations through pads, straps or other interfacing techniques. Improvements in actuator and sensor technology enabled the engineering of portable systems and the transition from academic to commercial applications. Medical exoskeletons provide the ability to move body parts for patients who are paralyzed below the waist. The possibility to enable movement requires the device to have a rigid structure, powerful actuators and sufficient control to ensure the stability of the patient. Such devices offer a potentially life-changing tool for patients by enabling them to stand or walk for short periods each day. Thus, many comorbidities, such as pressure sores, bone loss and muscle atrophy, can be reduced.

Exoskeletons have also been explored for assisting users in performing specific tasks more easily and/or for longer periods of time, or for endowing them with increased strength. In particular, active exoskeletons have been investigated for their potential to augment load carrying capacity. Such active devices consist of a supporting brace that is applied in parallel to the biological limb to transfer load to the ground; however, minimizing weight and power requirements of these systems remains a key challenge.

Soft wearable robots

Soft robotics is a rapidly growing research field that combines robotics and soft materials, such as elastomers and textiles. Soft robotic systems are engineered using low-cost fabrication techniques (for example, moulding and sewing), their morphology is adaptable and they are ideally suited for gripping and manipulating delicate objects. There is growing interest in the materials science, apparel, robotics and medical research communities in the field of soft wearable robots, as demonstrated by numerous special sessions and workshops at conferences across these fields. Compared to traditional rigid robots, soft robotic systems are inherently compliant and have a low weight. The compliant nature enables soft robots to safely interact with humans, for example, for medical and wearable applications.

The soft material properties provide a particular advantage for assisting with human motion by minimizing restrictions to the wearer and eliminating the need to carefully align a robot with biological joints. Textile anchors and flexible actuators can be used to interface a soft robotic device with the human body. Powered by actuation systems mounted to the body, forces can be created across joints to assist the underlying biological muscles. Thereby, the limb-worn components of wearable robots have very low inertia and, thus, do not restrict the natural movement of the wearer. However, the compliant nature of soft wearable robots also presents fundamental challenges in

John A. Paulson School of Engineering and Applied Sciences, Wyss Institute for Biologically Inspired Engineering, Harvard University, Cambridge, MA, USA.

e-mail: walsh@seas.harvard.edu

https://doi.org/10.1038/s41578-018-0011-1

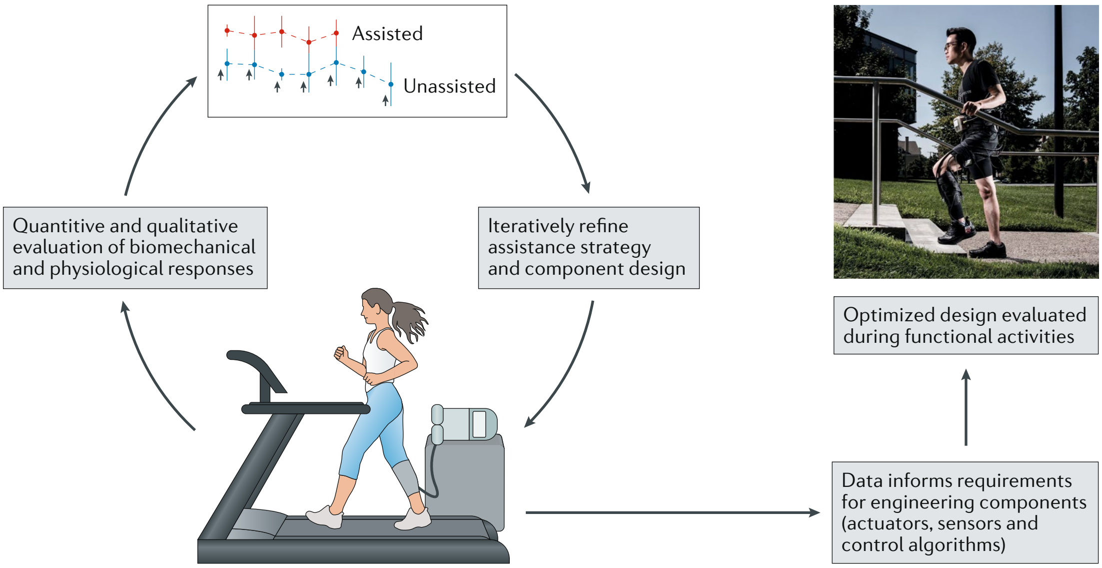

Fig. 1 | **Human-in-the-loop development of soft wearable robots.** The photograph is courtesy of Fred Merz, Rolex Foundation.

actuation, sensing, calibration, efficiency and control that need to be overcome to provide systems that benefit wearers.

Taking the human into the loop

The concept of providing low to moderate assistance using platforms with lightweight and non-restrictive components acting on limbs demands the wearer to adapt to the applied assistance. The rigid links and powerful motors enable a rigid exoskeleton to dominate the gait of the wearer and to enforce a walking pattern. However, when using soft wearable robots both the wearer and the robot contribute to the movement, requiring them to be in synchrony. Engineering tools need to be developed to tailor systems for different applications and individual patients, and importantly, there is a need to understand which joints and tissues (or combinations thereof) can benefit from assistance and the levels of force and power affecting component and system requirements. For example, how can the gait of a patient who has suffered a stroke be restored and what would be the best way of assistance? Should both legs get assistance and which joints should be addressed? What are the ideal actuator properties?

The development of soft wearable robots needs to take into account not only the technical performance of the components but also the entire human–robot system. To understand and determine the requirements for specific applications, studies involving human participants can be performed using versatile lab-based equipment. Different levels of assistance can be tested at a variety of locations, delivering data on the response of the wearer. Applying a human-in-the-loop approach enables the development of new technology, which is linked to an understanding of biological or pathological form and function, to investigate how humans adapt to robotic assistance. Thereby, development, component and system functions can be continuously evaluated and iteratively developed, and quantitative (robot, biomechanical and physiological) and qualitative (human factor) data can be collected (FIG. 1).

High impact applications

Initial progress in applying soft wearable robots has already been achieved with systems whose development has been guided by human subjects testing. For example, soft wearable robots can reduce the energy expenditure of healthy individuals during walking and running by augmenting normal muscle work through the application of assistive torques at the joints of the wearer. Initial studies applying varying assistance levels were first performed with lab-based equipment mounted beside a treadmill[1]. The development of autonomous systems (that is, fully body worn) has subsequently been informed by data obtained in the lab-based studies.

In addition to augmenting gait, soft wearable robots are also studied for their potential to improve mobility for patients with physical impairments, specifically patients suffering from spinal cord injury or stroke. A recent study demonstrated that the application of well-timed, small assistive forces to the paretic limb of stroke patients during walking has substantial biomechanical, energetic and cognitive benefits[2]. Soft wearable robots could also be used to restore the function of arms and hands in patients with upper extremity impairments, for example, by combining soft gloves with cables connected to fingers, driven by a number of motors[3], or soft fluid-powered actuators with movements matching those of the hand and arm[4]. Similar to approaches for the lower extremities, components interfaced with the arm are located on a wheelchair or mounted around the waist, thus adding minimal mass and restrictions to the limb.

Future perspective

The field of soft wearable robotics will impact fundamental and translational research in areas such as movement assistance, rehabilitation and injury prevention by developing lightweight systems that can be integrated into or worn under clothing and that do not restrict the user when unpowered. Most integrated systems that have already been tested on people were made of commercially available components, providing valuable knowledge for engineering and technology development to further refine wearable soft robotic components and systems. For example, new actuation schemes with high power-to-weight ratios that are optimized for generating low forces or modulating stiffness would be highly valuable to enable lightweight, low-power and low-profile systems. Additionally, to realize the vision of wearing such robotic systems like clothing, actuators and sensors manufactured with textile-based or textile-compatible materials will aid system integration. Such components are not yet commercially available; thus, the engineering, materials science and apparel communities need to collaborate to develop new material technologies for soft wearable robots.

The field is exploring a variety of applications, which necessitates new control approaches to target specific impairments. For example, some patients may need assistance with stability and others may benefit more from assistance with forward propulsion. Technology development is crucial, but it is equally important to investigate research in existing systems to advance the scientific understanding of how healthy and impaired individuals adapt to different assistance strategies.

Current soft wearable robots resemble the mechanism of rigid exoskeletons: they apply forces or torque to assist with the movement of the underlying biological muscle. However, embodiments of soft wearable robots operating with different mechanisms will emerge. For example, devices that apply compressive or shear forces to tissue on the inside or outside of the body to restore organ function[5] simulate the effects of massage, or supernumerary limbs or digits that enable new methods of human assistance and create opportunities for advanced human–machine interaction[6]. The field of soft wearable robotics is just beginning and will evolve based on a better understanding of the underlying fundamental science of soft robotics and the human–machine interaction.

1. Quinlivan, B. et al. Assistance magnitude versus metabolic cost reductions for a tethered multiarticular soft exosuit. *Science Robotics* **2**, eaah4416 (2017).
2. Awad, L. et al. A soft robotic exosuit improves walking in patients after stroke. *Sci. Transl Med.* **9**, eaai9084 (2017).
3. Kang, B. B. et al. Development of a polymer-based tendon-driven wearable robotic hand. *2016 IEEE International Conference on Robotics and Automation (ICRA)* 3750–3755 (2016).
4. Polygerinos, P. et al. Soft robotic glove for combined assistance and at-home rehabilitation. *Robotics and Autonomous Systems (RAS) Special Issue on Wearable Robotics* **73**, 135–143 (2015).
5. Roche, E. et al. Soft robotic sleeve supports heart function. *Sci. Transl Med.* **9**, eaaf3925 (2017).
6. Wu, F. Y. & Asada, H. H. Implicit and intuitive grasp posture control for wearable robotic fingers: a data-driven method using partial least squares. *IEEE Trans. Robotics* **32**, 176–186 (2016).

Acknowledgements
This Comment is based on knowledge gained from working with a fantastic multidisciplinary team and collaborators with backgrounds in robotics, functional apparel design, industrial design, material science, manufacturing, biomechanics and physical therapy as well as generous support from Defense Advanced Research Projects Agency (DARPA), the National Science Foundation and the National Institutes of Health.

Competing interests
The author is listed as a co-inventor on patents and patent application filed by Harvard University that cover soft wearable robot concepts. In addition, Harvard University has entered into a licensing and collaboration agreement with ReWalk Robotics and the author is a paid consultant to ReWalk Robotics.