Introduction to the Special Section on Wearable Robots

WEARABLE powered robots may be used for functional substitution in patients suffering from motor disorders, rehabilitation, assistance, and strength augmentation. Despite recent technological and scientific achievements, more research is needed to realize the promise of intuitive, easy-to-wear, safe, and effective wearable robots. Directions of current technical innovation and future trends include the following.

1) Improved Sensing, Actuation, and Computation: New technologies are enabling better sensing and interpretation of human–robot interaction, new actuators are enabling better interaction, and enhanced computing power is enabling complex reasoning and control strategies. In particular, the emerging area of soft wearable robots has started to see exciting results from studies with various populations. There are now commercially available soft wearable rehabilitation robots for the lower and upper extremity of subjects who have suffered a stroke. In addition, soft exosuits for the back help workers perform physically strenuous tasks in industry, alleviating injuries and providing a safer work environment.

2) Better Assessment: Currently, we lack standardized frameworks for evaluating the effectiveness of wearable robots, but this is beginning to change. The European H2020 EUROBENCH project aims to create the first European benchmarking framework for robotic systems including (but not limited to) bipedal robotic technologies, i.e., humanoids and lower limb wearable robots. To reach this goal, the EUROBENCH consortium must develop the experimental facilities and software tools to measure system ability levels in a rigorous, quantitative, and replicable way. In the United States, ASTM International's Exo Technology Center of Excellence (ET CoE) brings together industry, healthcare, academia, and government to accelerate safety and reliability standards for exoskeletons. Through research-to-standards, knowledge sharing, and education efforts, the ET CoE will ensure greater confidence in the baseline performance of exoskeletons and drive faster commercialization and adoption.

3) Comfort and Safety: Effective, safe, and comfortable transfer of mechanical power between an exoskeleton and a user is still an open challenge in the field of wearable robots. Two primary research thrusts within this topic are 1) effective coupling of the human and the wearable robot and 2) appropriate actuators for wearable robots. Within 1), research on exoskeletons with rigid links focuses on novel mechanisms to compensate for human–robot joint axes misalignment. Research on soft exosuits focuses on fabric-based technologies that offer comfortable anchoring to the human body. Within 2), brushless DC motors are being coupled to innovative transmissions and elastic elements to achieve high torque density, low output impedance, and force sensing.

4) Combining Wearable Robots With Functional Electrical Stimulation (FES) and Spinal Cord Stimulation (SCS): The combination of a robotic exoskeleton with FES or SCS is known as a hybrid exoskeleton or hybrid neuroprosthesis. In these hybrid systems, limb motion and forces are achieved by a combination of wearable robot torques and body forces induced by stimulation of peripheral muscles (FES) or the spinal cord (SCS). For example, therapy using wearable robots in conjunction with SCS and weight support may improve outcomes in retraining walking patterns. Additional research is needed to determine how best to coordinate muscle activation via SCS or FES in cooperation with wearable robots.

5) Adaptive Control and Learning: Currently, prosthesis adaptation to individual users, in daily walking environments and tasks beyond cyclic locomotion, has not been fully demonstrated. Optimal adaptive control is needed to maximize performance for individual users. Recently, advanced control algorithms (such as human-in-the-loop optimization, reinforcement learning, continuous phase control, etc.) have been developed to address these gaps. Future research should address formulation of optimization goals for lower limb prosthetics, design of wearable sensors and hardware for algorithm implementation and daily practice, and deployment of optimal adaptive controllers for safe day-to-day operation. Similar research challenges also apply to lower limb exoskeletons, and lessons learned from robotic prostheses can be extended to exoskeletons and other assistive machines.

As wearable robot technology advances to become more suitable for use outside of a laboratory setting, new sensing and control strategies will be crucial to ensure synergistic interaction with the user. Approaches for noninvasively monitoring muscle and neural activity (e.g., ultrasound and near infrared spectroscopy) will enable researchers to infer the intent of the wearer and better understand how individuals adapt to assistance. Data-powered machine learning models will provide a valuable tool for estimating important biomechanical metrics, which cannot be accurately measured by existing sensors. Finally, new sensing and estimation approaches for understanding interaction forces and transfer of power between wearable robots and the human body will lead to new control approaches and assist in interpreting results from biomechanical studies.

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This Special Section on Wearable Robots

The call for contributions to this special section received an impressive response from the community. A total of 40 abstracts were submitted, from which 25 submissions were encouraged. Ten of these submissions were accepted and are being published in this special section. Topics covered in these papers span the research areas described previously, and include the core technologies for the design of soft robotic suits, novel optimization approaches for human-in-the-loop control of exoskeletons, mechanical solutions for upper limb wearable robots and cable-driven exosuits, analyses of myoelectric control as an alternative to force control of exosuits, human-in-the-loop optimization of assistance, adaptive controllers for powered prostheses, torque control of lightweight direct-drive exoskeletons, mechanical designs to compensate joint misalignments, and neuromechanical modeling approaches to adaptive control of bilateral ankle exoskeletons.

In [A1], Xiloyannis *et al.* review the modes of actuation, the physical human–robot interface, and the intention-detection strategies of state-of-the-art soft robotic suits, highlighting the advantages and limitations of different approaches. The paper also discusses the use of soft robotic suits for augmenting human function and compensating motor impairments.

In [A2], Lotti *et al.* compare two different and complementary controllers on a wearable robotic suit: a model-based myoelectric control (myoprocessor), which estimates the joint torque from the activation of target muscles, and force control that estimates human torques using an inverse dynamics model. The results suggest comparable performance in augmenting muscular activity.

In [A3], Durandau *et al.* propose a new human–machine interface to drive bilateral ankle exoskeletons during a range of walking conditions. The proposed approach uses person-specific neuromechanical models of the human body to estimate biological ankle torques in real-time from electromyograms and joint angles. The ankle exoskeleton controller uses these estimates to control the ankle exoskeleton. Results show a decrease in biological ankle torques as well as in ankle muscle EMGs.

In [A4], Park *et al.* propose a method to adjust gait parameters of powered exoskeletons for subjects with a spinal cord injury. Instead of directly setting predefined joint reference trajectories, the controller iteratively calculates a targeted trunk inclination angle based on ground timing information. The results provide evidence of the effectiveness of the proposed method to enable independent walking in two subjects assisted by the suit, with positive impact on walking speed, oxygen consumption, hand force on crutches, and other metrics.

In [A5], Gordon *et al.* deal with the identification of subject-specific exoskeleton control strategies using human-in-the-loop optimization, and in particular, explores how musculoskeletal modeling techniques can be used to make this process more efficient. The results of this paper contribute to the design of personalized control strategies to maximize the effectiveness of wearable robots.

In [A6], Hood *et al.* present an adaptive stair ascent controller that enables users of powered knee and ankle prostheses to negotiate stairs of diverse stair heights at a self-selected cadence. The proposed controller modulates the injection of energy during the stance phase based on a continuous adaptation of the knee joint torque–angle relationship. The results of this paper validate the functionality of the stair ascent controller for an above-knee amputee user of the Utah Lightweight Leg.

In [A7], Huang *et al.* present a study of the benefits of a high-performance knee exoskeleton using stiffness modeling and advanced control methods for continuous torque assistance. The work proposes a continuous torque controller that estimates the biological torque in real-time and is adaptable to different overground walking speeds.

In [A8], Park *et al.* present a novel exoskeleton to assist the shoulder movement of workers performing overhead manipulations tasks. Two innovative mechanisms to compensate for human–robot axis misalignments are presented. One mechanism (called the center-of-rotation tracking mechanism) compensates for the misalignment caused by the scapulohumeral rhythm. A second mechanism (called the force-guiding mechanism) compensates for the horizontal misalignment due to changes in the plan of the arm elevation. The results show the mechanisms are effective at reducing the effects of joint misalignment.

In [A9], Dragusanu *et al.* propose a modular hand/wrist exoskeleton that actuates finger flexion/extension motions and wrist flexion/extension and adduction/abduction motions. The paper introduces the main features of the device and presents tests conducted with a user with limited hand and wrist mobility.

Finally, in [A10], Li *et al.* propose a new exosuit that allows the user to move over a wide range of lumbar trajectories. A biomechanical analysis is conducted to map assistive cable forces to effective lumbar torque assistance, allowing for intuitive controller design in the lumbar joint space. Human subject experiments illustrate the potential for the device to reduce lumbar injury risk.

We, the guest editors, would like to thank the authors for submitting their work to this special section. We are confident that many of these papers will come to be recognized as seminal contributions to the fast-growing field of wearable robotics.

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APPENDIX
SPECIAL SECTION ARTICLES

[A1] M. Xiloyannis *et al.*, "Soft robotic suits: State of the art, core technologies, and open challenges," *IEEE Trans. Robot.*, vol. 38, no. 3, pp. 1343–1362, Jun. 2022.

[A2] N. Lotti *et al.*, "Myoelectric or force control? A comparative study on a soft arm exosuit," *IEEE Trans. Robot.*, vol. 38, no. 3, pp. 1363–1379, Jun. 2022.

[A3] G. Durandau, W. F. Rampeltshammer, H. van der Kooij, and M. Sartori, "Neuromechanical model-based control of bi-lateral ankle exoskeletons: Biological joint torque and electromyogram reduction across walking conditions," *IEEE Trans. Robot.*, vol. 38, no. 3, pp. 1380–1394, Jun. 2022.

[A4] K.-W. Park, J. Choi, and K. K. Kong, "Iterative learning of human behavior for adaptive gait pattern adjustment of a powered exoskeleton," *IEEE Trans. Robot.*, vol. 38, no. 3, pp. 1395–1409, Jun. 2022.

[A5] D. F. N. Gordon, C. McGreavy, A. Christou, and S. Vijayakumar, "Human-in-the-loop optimization of exoskeleton assistance via online simulation of metabolic cost," *IEEE Trans. Robot.*, vol. 38, no. 3, pp. 1410–1429, Jun. 2022.

[A6] S. Hood, L. Gabert, and T. Lenzi, "Powered knee and ankle prosthesis with adaptive control enables climbing stairs with different stair heights, cadences, and gait patterns," *IEEE Trans. Robot.*, vol. 38, no. 3, pp. 1430–1441, Jun. 2022.

[A7] T.-H. Huang *et al.*, "Modeling and stiffness-based continuous torque control of lightweight quasi-direct-drive knee exoskeletons for versatile walking assistance," *IEEE Trans. Robot.*, vol. 38, no. 3, pp. 1442–1459, Jun. 2022

[A8] D. Park, S. Toxiri, G. Chini, C. D. Natali, D. G. Caldwell, and J. Ortiz, "Shoulder-sideWINDER (shoulder-side wearable industrial ergonomic robot): Design and evaluation of shoulder wearable robot with mechanisms to compensate for joint misalignment," *IEEE Trans. Robot.*, vol. 38, no. 3, pp. 1460–1471, Jun. 2022.

[A9] M. Dragusanu, M. Z. Iqbal, T. L. Baldi, D. Prattichizzo, and M. Malvezzi, "Design, development, and control of a hand/wrist exoskeleton for rehabilitation and training," *IEEE Trans. Robot.*, vol. 38, no. 3, pp. 1472–1488, Jun. 2022.

[A10] J. M. Li, D. D. Molinaro, A. S. King, A. Mazumdar, and A. J. Young, "Design and validation of a cable-driven asymmetric back exosuit," *IEEE Trans. Robot.*, vol. 38, no. 3, pp. 1489–1502, Jun. 2022.

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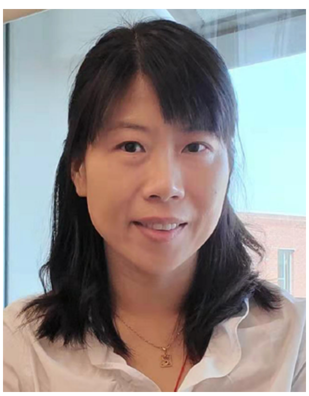

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