Wearable Robotics

By Rocco Vertechy and Dino Accoto

A wearable robot (WR) is a machine placed in a close fit with the human body, thereby moving and working in synchrony with its limbs [1]–[4]. The large (and growing) family of WRs includes hard exoskeletons and soft exosuits, worn in parallel with the user's body to augment its performance, and active limb prostheses, which, when worn in series to the user's body, replace missing extremities.

WRs make it possible to realize a tightly integrated human–robot system that can help perform many daily activities, while preserving the intelligent supervision by its human wearer [1], [5].

There are several intended uses of WRs, including teleoperation [6] and physical support during locomotion [7]–[10] or object handling [11]–[13]. Practical applications range from the daily assistance of elderly or disabled people and heavy-duty workers to the functional rehabilitation and restoration of lost functions.

Although devices like Cartesian manipulators, wheelchairs, and cranes already exist for such applications, none of them is flexible enough to be adapted to very different usage scenarios, nor are they fully satisfactory from the point of view of ergonomics and autonomy. WR technologies should be minimally invasive and user specific, i.e., not intended for a whole class of people but tailored to the specific user, like an haute couture dress, to optimally enhance residual sensorimotor capabilities, thus creating an intimate interaction.

Propelled by the U.S. Defense Advanced Research Projects Agency's Exoskeletons for Human Performance Augmentation Program, Revolutionizing Prosthetics Program, and Warrior Web Program as well as by other research programs across Europe and Asia, significant advances have occurred in the last decade in the field of WRs, which are now significantly boosting the interest from the industry and the media [14]–[18].

To date, after about a century from their original conception, several active limb prostheses are in use and on the market, a number of active exoskeletons are in the process of field demonstration and assessment, and the first active exosuits are being developed and tested in laboratories. However, the development of a complete and functional WR remains a challenging task that deserves innovations in numerous disciplines, including ergonomics, kinematics, dynamics, actuation, interaction control, and energetics.

This special issue of *IEEE Robotics and Automation Magazine* (edited by Rocco Vertechy, Dino Accoto, and Hugh Herr) collects recent works on the development of WRs, with the aim of presenting the latest results and methodologies that can assist the practicing engineer in the design, control, and validation of soft exosuits, hard exoskeletons, and prostheses.

Although there is a strong need for significant progress in many disciplines, the focus of this special issue is on complete and fully functional systems, not on subsystems or components. This choice is motivated by the fact that WRs are complex (biomechatronic) systems, in which parts must be designed to be integrated harmoniously with each other and with the biological system with which they interact (i.e., the body of the wearer). Overall, this special issue comprises eight articles, reporting on:

- one exosuit for the legs
- four hard exoskeletons
  - one for the whole body
  - two for the legs
  - one for the arm
- three lower-limb prostheses.

The first article, "Stronger, Smarter, Softer" reports on the development and evaluation of an active soft exosuit for human walking assistance, which results from the integration work by experts in textiles, controls, biomechanics, and mechanical engineers. The presented exosuit does not provide external load transfer and is designed to supply the wearer's joints with a fraction of the nominal torques that are required for level walking. Results from walking experiments are provided to show the kinematic, kinetic, and energetic performances of the proposed system.

The second article, "The Body Extender," presents the development and validation of an active exoskeleton for the transport and handling of heavy loads. The exoskeleton comprises active legs and arms and features a modular hardware and open software architecture, which make it possible to reprogram and reconfigure it to conduct

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Figure 1. A soft exosuit for locomotion assistance (photo courtesy of the Harvard Biodesign Lab).

Figure 2. A full-body hard exoskeleton for human power augmentation (photo courtesy of PERCRO Laboratory, Scuola Superiore Sant'Anna).

Figure 3. A powered knee–ankle prosthesis for transfemoral amputees (photo courtesy of Brian Lawson, Vanderbilt University).

studies on complex human–exoskeleton interaction. Experimental results are provided to show the effectiveness of the system in activities such as walking, squatting, and heavy-load handling.

The third article, "Robomorphism" describes the design methodology, development, and validation of an active lower limb orthosis. The system features a nonanthropomorphic kinematic architecture and series-elastic actuation, which make it possible to improve system wearability and transparency.

The fourth article, "XPED2," presents the development and validation of a passive lower-limb exoskeleton for locomotion assistance. The system features a lightweight structure. The robot does not comprise actuators and uses multiarticular exotendons to transfer energy between joints. Results from walking experiments are reported to show the kinematic, kinetic, and energetic performances of the proposed system. A comparison of experimental results with theoretical predictions highlights the importance of experimental investigations, especially to understand the biological mechanisms having an impact on the metabolic cost of walking.

The fifth article, "Bilateral Robot Teleoperation," describes a complete telerobotic system that is composed of an upper-limb master exoskeleton and a Kuka lightweight robot slave. The system features force-reflection to the operator and a graphical touch-screen interface, which makes the system usable by untrained operators. The master is completely portable and intuitive both in terms of robot control and system operation. Experimental results are provided to show the ability of the proposed system in rendering different stiffness contacts.

The sixth article, "A Robotic Leg Prosthesis," presents the development and validation of an integrated active lower-limb prosthesis, designed to emulate a generalizable mechanical behavior and to modify it in real time as governed by the prosthesis controller. After describing the hardware design, the authors describe a hybrid controller that provides coordination for level walking. Results from walking experiments are reported to show the kinematic and kinetic performances of the system. A comparison of experimental results with healthy joint biomechanical data is also provided.

The seventh article, "CYBERLEGs," describes the development and validation of a lower-limb prosthesis that integrates an active ankle and a passive knee. The ankle features a variable-compliance actuator. The knee features one mechanism for stiffness regulation and a second mechanism that makes it possible to transfer energy between the knee and ankle. The authors describe a finite-state controller for level walking based on intention detection. Results from walking experiments are reported to show the kinematic and kinetic performances of the proposed prosthesis and controller, along with the adequacy of the considered intention-detection algorithm.

The last article, "Speed-Adaptation Mechanism," presents an integrated knee–ankle prosthesis prototype with a novel controller. By offline encoding the quasi-stiffness profiles of intact legs in the stance controller, the proposed controller makes it possible to imitate the basic speed-adaptation mechanism used by intact legs and enables the active

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paradigm for real-time control. Basically this amounts to a low-level, real-time, hardware-based control and a high-level control that is not guaranteed to be real time. They follow the same approach as in the National Aeronautics and Space Administration/National Bureau of Standards Standard Reference Model Telerobot Control System architecture, breaking the problem down into six basic elements: 1) actuators, 2) sensors, 3) sensory processing, 4) world modeling, 5) behavior generation, and 6) value judgment. These are integrated into a multilevel hierarchical structure. Finally, the authors describe an underwater object recovery mission application demonstration of their system. Each phase was successfully completed with no human intervention.

The conclusion of this book describes the careful addressing of issues that appear repeatedly in autonomous robotic manipulation (of all areas). These are target area navigation, vehicle positioning, and arm control systems.

Although there are many open issues for fully autonomous robots capable of handling unstructured environments and missions, this book provides an insightful big-picture approach that could be applied to many problems. Robotic systems capable of operating autonomously in disasters and emergencies will need this type of complete solution strategy. This book is a step in the right direction toward addressing this increasingly pressing need.

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prosthesis to achieve biologically accurate kinematics and kinetics across different walking speeds, without the need for speed- or patient-specific tuning. Results from walking experiments are reported to show the effectiveness of the proposed control approach.

There are many ongoing initiatives dedicated to wearable robotics, including conferences, special issues, and international workshops. All of them demonstrate the growing interest in the topic. Overcoming the physical limits of the body, whether natural, age-induced, or caused by diseases or traumatic events, with temporary or permanent effects, is an actual societal need. Finally, considering its highly inter- and transdisciplinary nature, the value of wearable robotics for the education of young engineers should not be overlooked.

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