Wearable Robots

Antonio Frisoli
PERCRO Laboratory, TeCIP Institute, Scuola
Superiore Sant'Anna, Pisa, Italy

Synonyms

Body extender; Exoskeletal robots; Exoskeletons; Human amplifying robot; Powered exoskeletal harness; Powered orthoses; Prosthesis; Prosthetic robot

Definition

Wearable robots are advanced human symbiotic robotic systems characterized by suitable shape, kinematic, and weight factors to be worn on the human body with the function of either augmenting and assisting (exoskeletons) or restoring human limb function (prosthetic robots) (Pons 2008).

When they are shaped in the form of powered orthoses, they are typically called exoskeletons, where in biology the term exoskeleton ("*exo*-" prefix stands for outer) is used to refer to the outer structure protecting insects body, so that in analogy exoskeletons are robotic structures that can be put on existing limbs. When they substitute a missing human limb, they are called prosthetic robots.

Overview

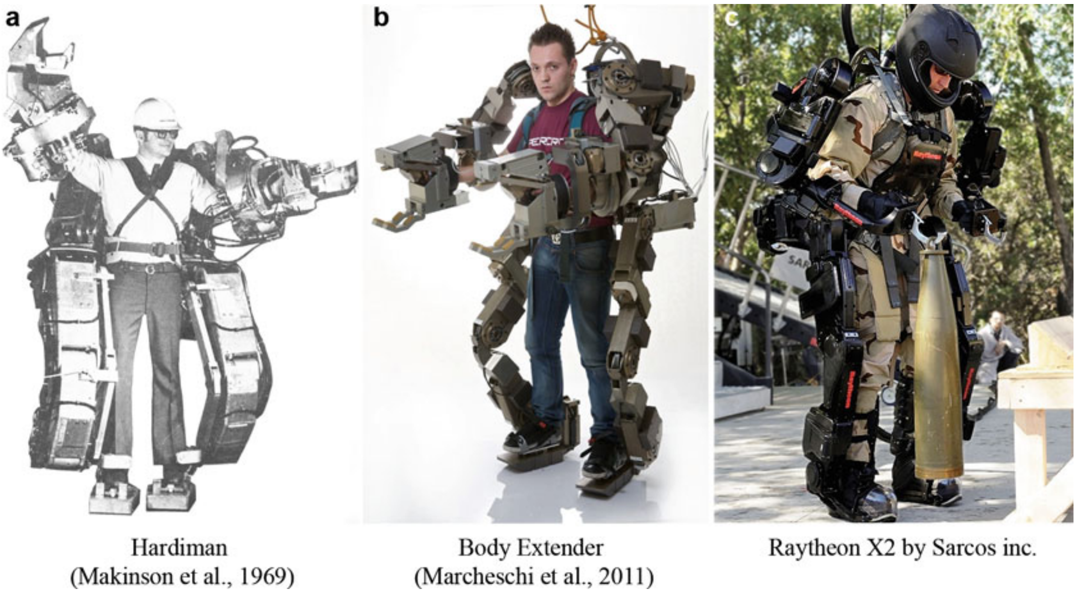
Human beings have always pursued the dream of enforcing human capabilities through the usage of wearable devices.

If we consider prostheses, the earliest records date back to 77 AD when Roman scholar, Pliny the Elder, described how, Marcus Sergius, a Roman general, after losing a hand in war, received a prosthesis that enabled him to return successfully to battle (Zuo and Olson 2014), but in the early 1900s, Giuliano Vanghetti was the first scientist to propose an invasive prosthesis directly connecting to the internal dynamics of the arm to generate movement, i.e., the prosthesis was directly linked with muscular and tendinous loops (Tropea et al. 2017).

To date the first example of wearable robot for empowering human strength was made in the 1970s by General Electric, with the Hardiman project, aiming at implementing a full body extender to enforce human capabilities (Makinson et al. 1969) (see Fig. 1a). At that time, the exoskeleton was based on hydraulic actuation with already implemented a bilateral (force reflecting) controller, but unfortunately the project was discontinued for safety issues.

The first robotic exoskeletons were then built for needs in the area of teleoperation and space applications (Bergamasco et al. 1994), in the context of bilateral teleoperation. The sector of exoskeletons received a great impetus and boost in the twenty-first century from Darpa exoskeleton research program to support the development

M. H. Ang et al. (eds.), *Encyclopedia of Robotics*,
https://doi.org/10.1007/978-3-642-41610-1_22-1



Wearable Robots, Fig. 1 Examples of human amplifiers exoskeletons, image credits (**b**) prof. Massimo Bergamasco, Scuola Superiore Sant'Anna, (**c**) Sarcos Inc.

of soldier amplification capabilities, and then it subsequently raised up an increasing interest in the medical sector with the development of active lower limb exoskeletons for walking assistance in spinal cord injury and upper limb exoskeletons for stroke rehabilitation.

Applications

Wearable robots have found so far their application in a large variety of tasks, ranging from rehabilitation and assistance up to human power augmentation. According to the field of application and their features, we can distinguish between powered exoskeletons, upper limb exoskeletons (ULEs) and lower limb exoskeletons (LLEs), and robotic prostheses for limb replacement.

Exoskeletons

Full body exoskeletons can be used for human power augmentation, in order to increase human capability in the execution of heavy duty tasks, ranging from amplifying machines capable of lifting loads up to 100 kg (Marcheschi et al. 2011) to lower limb exoskeletons that can provide support to soldiers during long-distance walks, e.g., Fig. 2c.

A wider category of exoskeletons have been proposed for the reduction of fatigue during the execution of low duty tasks in the industry, e.g., highly repetitive handling of loads up to 20 kg, to prevent the onset of injury at the level of the muscle-skeletal system, for instance, by safely transferring the loads from upper limbs to the trunk or the legs. The assistance can be also provided at level of single articulation only, e.g., to relieve fatigue during walking with hip, knee, or ankle "exo-modules": recently it has been validated how walking effort, measured in terms of metabolic consumption, is reduced by the adoption of powered ankle push-off (Caputo and Collins 2014).

In the medical domain, exoskeletons are applied both for rehabilitation and training in neuromotor rehabilitation, i.e., ULEs for rehabilitation after stroke (Frisoli 2018) or LLEs for assistance to paraplegia after spinal cord injury (Donati et al. 2016). Soft ULEs (Chiaradia et al. 2018) and LLEs (Wehner et al. 2013) have also been proposed as solutions for regain and

Wearable Robots, Fig. 2 Some examples of ULEs and LLEs. (**a**) The Alex exoskeleton (Pirondini et al. 2016). (**b**) CADEN-7 exoskeleton (Perry et al. 2007). (**c**) Hulc Exoskeleton (Zoss et al. 2006). (**d**) Nasa X1 Exoskeleton (Rea et al. 2013)

amplification of human strength or rehabilitation training, while selective rehabilitation training can be performed with hand or finger assistive devices (Leonardis et al. 2015; Sarac et al. 2017)

Prosthetic Robots

An “ideal” satisfactory prosthetic robot should be easy to control, comfortable to wear with good body interface and correct weight inertia, and biocompatible (Lai et al. 2007). The challenge in the design of prosthetic robots relies so in the high level of integration with the human body that needs to be achieved, so that while exoskeletons work in parallel with human body, prosthetic wearable robots operate mechanically in series (Pons 2008). Bioinspiration and biomimetics are two common design principles used to fulfill the above requirements.

In the field of lower limb prostheses (LLPs), the design features of wearable robotic legs are derived from study of neuromechanical models of human locomotory function to achieve robots that move like, and feel like, their biological counterparts (Bergamasco and Herr 2016). For instance, it is well known that during walking cycle, human ankle is varying its impedance, so a biomimetic actuator architecture should be designed to match similar biologic levels of powered plantar flexion at the ankle. Current prosthetic designs make use of series and parallel elastic actuation for power amplification in order to reduce the cost of transport (COT) and to improve the comfort and performance of walking (Fig. 3).

Key Research Findings

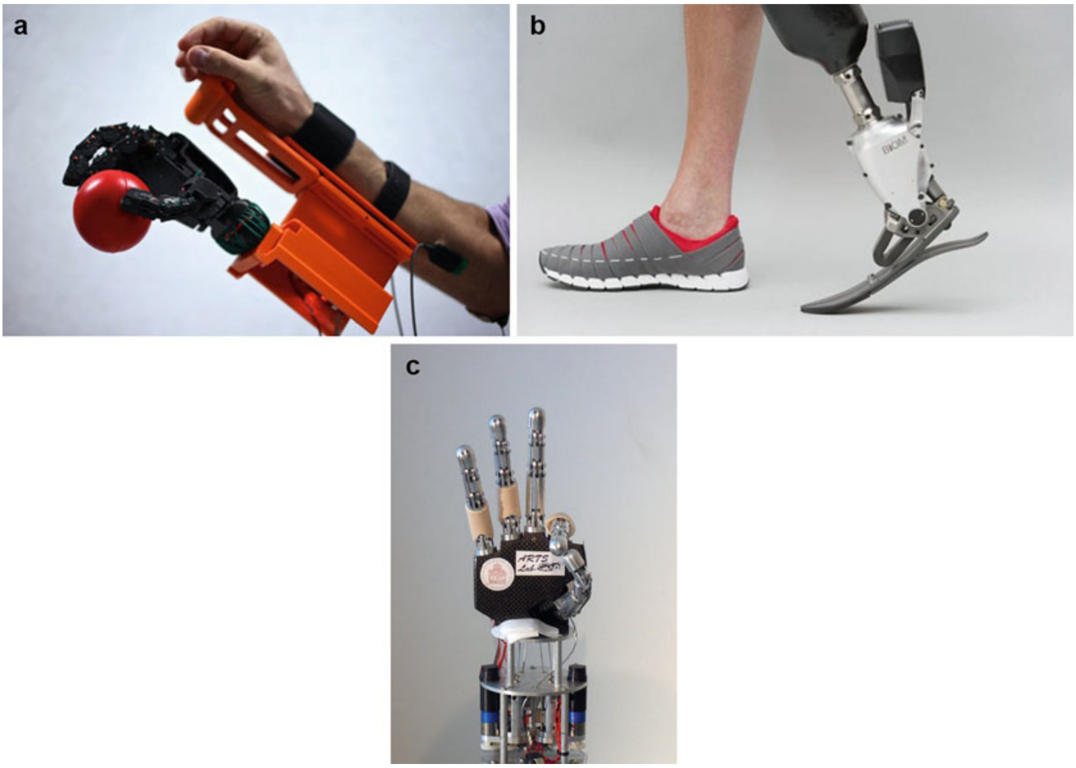
Exoskeletons

One peculiar feature of exoskeletons is that they act in symbiosis with the human operator, being able to follow his/her intention of movement. This poses specific requirements at the level of control, actuation, and kinematics.

Control

In order to be able to provide high-fidelity force feedback and unperturbed movement of the human upper extremity, exoskeleton actuation systems should be designed to maximize their Z-width as it happens with haptic devices (Colgate and Brown 1994), which implies a control bandwidth higher than human reaction time to prevent instability during human-in-the-loop control.

Based on the adopted actuation and control, robotics exoskeletons can be classified as impedance-based design (open-loop or force closed-loop control impedance control) or admittance-based design (admittance control with position feedback).



Wearable Robots, Fig. 3 Example of ULP and LLP prosthetic robots. (**a**) Soft hand (Catalano et al. 2014). (**b**) Biom by IWalk (Blaya and Herr 2004). (**c**) Cyber hand (Zollo et al. 2007)

Kinematic Compatibility

In order to assist human motion, exoskeletons should be accurately designed from an ergonomic and biomechanical point of view. In particular since the real anatomy of human joints does not correspond to ideal rotational or spherical joints, axes misalignment can lead to undesired interaction loads (UI loads) that can render wearable robots uncomfortable (Jarrasse and Morel 2012). Exoskeletons need to have either appropriate size adjustment mechanisms to fit with human individual dimensions or to be endowed with a number of passive joints in the kinematic chain connecting the robot links with the human limbs. The number of passive dofs can be computed considering that the number of degree of freedom F is constrained by the formula (Li et al. 2017) $F = f_{\text{active}} + f_{\text{human}} + f_{\text{passive}} - dl$, where f indicates the number of dof for active, passive, and human arm joints, l is the number of kinematic loops, and $d = 6$ for spatial kinematics.

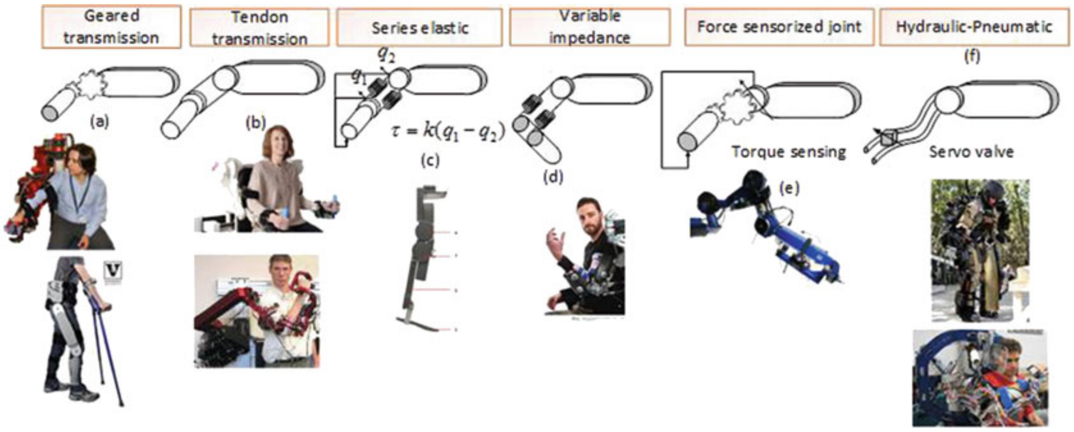
Actuation

In terms of actuation, exoskeletons built for rehabilitation, and human power augmentation make use of different actuation solutions, as outlined in Fig. 4.

As far as powered exoskeletons, both Berkeley Lower Extremity Exoskeleton (BLEEX) (Zoss et al. 2006) and the XOS exoskeleton (Sarcos Research Corporation Inc., USA) are based on hydraulic actuation systems, with control algorithms based on force measurements for a smooth control of exoskeleton movement, while both Robot Suit HAL (Kasaoka and Sankai 2001) and the Body Extender (Marcheschi et al. 2011) make use of electrical motors.

ULEs for medical applications have been mainly built with pneumatic actuation (Kousidou et al. 2007; Sanchez et al. 2005) and electrical actuation for safety issues. Electrical actuators might differ for the adoption of geared drive solutions (Nef and Riener 2005), joint torque controlled actuators by force closed-loop control (Vertechy et al. 2009), tendon drive (Perry et al. 2007; Ruffaldi et al. 2014; Frisoli et al. 2005), or mixed designs where a combination of ball screws and cable is used (Garrec et al. 2008).

As for LLEs, the most represented class among the walking assistive orthoses for the paraplegics is the “mechanically assisted body position controlled” exoskeletons, to which belong the Ekso (by Ekso Bionics) derived from E-legs (Strausser and Kazerooni 2011); the Indego, descending from the Vanderbilt HK orthosis (Quintero et al. 2011); and the Rewalk (Argo Medical Technologies Inc).



Wearable Robots, Fig. 4 Main actuator solutions adopted for ULEs and LLEs, from left to right Armin (Nef and Riener 2005), Indego (Quintero et al. 2011), Alex 3 (Ruffaldi et al. 2014), Caden-7 (Perry et al. 2007), Symbitron exoskeleton (van der Kooij et al. 2017), NEUROExos (Lenzi et al. 2011), Rehab-Exos (Vertechy et al. 2009), Pneu-Wrex (Sanchez et al. 2005)

Alternatively soft exoskeletons make use of actuation principles that can be either embedded in garments (Cappello et al. 2016), e.g., sheathed tendons, or in deformable structures (Polygerinos et al. 2015), e.g., pneumatic inflatable structures, with a consequent reduction of weight of moving parts and a distributed actuation concept.

On the other side in the context of research, other exoskeleton designs have been proposed based on VSA (Variable Stiffness Actuators) actuators, or more generally VIA (Variable Impedance Actuators). However the usage of VSA is quite limited for issues of portability, since each actuated joint requires two motors to control both stiffness and motion; one example is the NEUROExos (Lenzi et al. 2011). Series elastic actuation (SEA), where an electric motor is coupled with a spring with fixed stiffness, is much more used since they allow to achieve a precise control of joint torque. The LOPES exoskeleton (Veneman et al. 2007) has been the first exoskeleton using serial elastic actuation and then adopted later also in Symbitron LLE (van der Kooij et al. 2017) and other designs.

Prostheses

In the field of upper limb prostheses (ULPs), significant advances have been achieved both in terms of design and control. Underactuation has been adopted in prosthetic hands as an approach to simplification of complexity in design and control (Zollo et al. 2007; Cabas and Balaguer 2005), where basically a differential transmission is associated to control multiple joints with one single actuator, typically implemented by means of a cable routed over a set of joint idler pulleys at joints. More recently the soft hand (Catalano et al. 2014) has reduced the dimensionality of the grasping problem by combining underaction with soft motion synergies, i.e., primitive of human movements derived from human grasping observation in manipulation tasks. As far as control, since the 1950s, the surface EMG has been traditionally the main biometric signal for control of multifunction upper limb prosthesis in practical use (Jiang et al. 2012). Nowadays both targeted muscle reinnervation, e.g., the rerouting of residual nerves of the amputees over the chest muscles transforming them into a "*biological signal amplifier*" (Farina et al. 2014), and neuroprostheses, i.e., neural interfaces for the peripheral nervous systems (Raspopovic et al. 2014), have been successfully used to allow amputees to control multi-dof hand prostheses.

Future Directions

Wearable robotics is an emerging and rapidly growing research field. Several new lines of research are stemming out to overcome current limitations of existing robots, and future directions are concerned with energy harvesting and high-density power storage for power generation for wearable robots, innovative human-robot interfaces for intuitive control with integrated sensory feedback, and advanced ergonomic designs for human symbiotic exoskeletons.

Brain-computer interfaces and electromyographic (EMG) signals have already been successfully used as noninvasive biometric measurements to trigger the initiation and control of movement in wearable robots in rehabilitation training (Frisoli et al. 2012), and future directions involve high-density EMG arrays and the application of motor synergies concept to reduce the dimensionality control problem.

Also the sensory feedback to amputees wearing prosthetic limbs or to paraplegics wearing exoskeletons is being investigated through sensory substitution, i.e., by providing suitable vibrotactile or more in general haptic stimulations to a different part of the body. Future research will be focused on completely implantable and long-term electronic system that by making use of intraneural electrodes, no larger than a human hair, can enable the motor signals sent by the brain to be transmitted to the robotic prosthesis and vice versa (Raspopovic et al. 2014).

In the field of LLEs for gait assistance, a strong limitation of existing systems is typically represented by the lack of self-balancing dynamic skills, which requires the patient to rely on crutches for maintaining the equilibrium.

The recent advances in the control of biped locomotion in humanoid robots will bring important results to achieve smooth dynamics balance control in exoskeletons as well.

Cross-References

- ▶ Haptics and Haptic Interfaces
- ▶ Human-Robot Collaboration
- ▶ Prosthesis Robotics
- ▶ Telerobotics

References

Bergamasco M, Herr H (2016) Human–robot augmentation. In: Siciliano B, Khatib O (eds) Springer handbook of robotics. Springer, Cham, pp 1875–1906

Bergamasco M, Allotta B, Bosio L, Ferretti L, Parrini G, Prisco G, Salsedo F, Sartini G (1994) An arm exoskeleton system for teleoperation and virtual environments applications. In: Robotics and Automation, 1994. Proceedings 1994 IEEE International Conference on. IEEE, pp 1449–1454

Blaya JA, Herr H (2004) Adaptive control of a variable-impedance ankle-foot orthosis to assist drop-foot gait. IEEE Trans Neural Syst Rehabil Eng 12(1):24–31

Cabas R, Balaguer C (2005) Design and development of a light weight embodied robotic hand activated with only one actuator. In: Intelligent Robots and Systems, 2005 (IROS 2005). 2005 IEEE/RSJ International Conference on. IEEE, pp 2369–2374

Cappello L, Binh DK, Yen S-C, Masia L (2016) Design and preliminary characterization of a soft wearable exoskeleton for upper limb. In: Biomedical Robotics and Biomechatronics (BioRob), 2016 6th IEEE International Conference on. IEEE, pp 623–630

Caputo JM, Collins SH (2014) Prosthetic ankle push-off work reduces metabolic rate but not collision work in non-amputee walking. Sci Rep 4:7213

Catalano MG, Grioli G, Farnioli E, Serio A, Piazza C, Bicchi A (2014) Adaptive synergies for the design and control of the pisa/iit softhand. Int J Robot Res 33(5):768–782

Chiaradia D, Xiloyannis M, Wilson Antuvan C, Frisoli A, Masia L (2018) Design and embedded control of a soft elbow exosuit. In: IEEE RoboSoft, the 1st IEEE Conference on Soft Robotics. IEEE

Colgate JE, Brown JM (1994) Factors affecting the z-width of a haptic display. In: Robotics and Automation, 1994. Proceedings, 1994 IEEE International Conference on. IEEE, pp 3205–3210

Donati AR, Shokur S, Morya E, Campos DS, Moioli RC, Gitti CM, Augusto PB, Tripodi S, Pires CG, Pereira GA et al (2016) Long-term training with a brain-machine interface-based gait protocol induces partial neurological recovery in paraplegic patients. Sci Rep 6:30383

Farina D, Jiang N, Rehbaum H, Holobar A, Graimann B, Dietl H, Aszmann OC (2014) The extraction of neural information from the surface EMG for the control of upper-limb prostheses: emerging avenues and challenges. IEEE Trans Neural Syst Rehabil Eng 22(4):797–809

Frisoli A (2018) Exoskeletons for upper limb rehabilitation. In: Sanguineti V, Colombo R (eds) Rehabilitation robotics – technology and applications, chap 6. Elsevier, Cambridge (MA), pp 75–85

Frisoli A, Rocchi F, Marcheschi S, Dettori A, Salsedo F, Bergamasco M (2005) A new force-feedback arm exoskeleton for haptic interaction in virtual environments. In: Eurohaptics Conference, 2005 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2005. World Haptics 2005. First Joint. IEEE, pp 195–201

Frisoli A, Loconsole C, Leonardis D, Banno F, Barsotti M, Chisari C, Bergamasco M (2012) A new gaze-bci-driven control of an upper limb exoskeleton for rehabilitation in real-world tasks. IEEE Trans Syst Man Cybern Part C Appl Rev 42(6):1169–1179

Garrec P, Friconneau J, Measson Y, Perrot Y (2008) Able, an innovative transparent exoskeleton for the upper-limb. In: Intelligent Robots and Systems, 2008. IROS 2008. IEEE/RSJ International Conference on. IEEE, pp 1483–1488

Jarrasse N, Morel G (2012) Connecting a human limb to an exoskeleton. IEEE Trans Robot 28(3):697–709

Jiang N, Dosen S, Muller K-R, Farina D (2012) Myoelectric control of artificial limbsis there a need to change focus? [in the spotlight]. IEEE Sig Process Mag 29(5):152–150

Kasaoka K, Sankai Y (2001) Predictive control estimating operator's intention for stepping-up motion by exoskeleton type power assist system hal. In: Intelligent Robots and Systems, 2001. Proceedings. 2001 IEEE/RSJ International Conference on, vol 3. IEEE, pp 1578–1583

Kousidou S, Tsagarakis N, Smith C, Caldwell D (2007) Task-orientated biofeedback system for the rehabilitation of the upper limb. In: Rehabilitation Robotics, 2007. ICORR 2007. IEEE 10th International Conference on. IEEE, pp 376–384

Lai J, Schoen M, Gracia AP, Naidu D, Leung S (2007) Prosthetic devices: challenges and implications of robotic implants and biological interfaces. Proc Inst Mech Eng H J Eng Med 221(2):173–183

Lenzi T, Vitiello N, De Rossi SMM, Roccella S, Vecchi F, Carrozza MC (2011) Neuroexos: a variable impedance powered elbow exoskeleton. In: Robotics and Automation (ICRA), 2011 IEEE International Conference on. IEEE, pp 1419–1426

Leonardis D, Barsotti M, Loconsole C, Solazzi M, Troncossi M, Mazzotti C, Castelli VP, Procopio C, Lamola G, Chisari C et al (2015) An EMG-controlled robotic hand exoskeleton for bilateral rehabilitation. IEEE Trans Haptics 8(2):140–151

Li J, Zhang Z, Tao C, Ji R (2017) A number synthesis method of the self-adapting upper-limb rehabilitation exoskeletons. Int J Adv Robot Syst 14(3):1729881417710796

Makinson JB, Bodine DP, Fick BR (1969) Machine augmentation of human strength and endurance hardiman i prototype project. Technical report, General Electric Technical Report S-71-1056

Marcheschi S, Salsedo F, Fontana M, Bergamasco M (2011) Body extender: whole body exoskeleton for human power augmentation. In: Robotics and Automation (ICRA), 2011 IEEE International Conference on. IEEE, pp 611–616

Nef T, Riener R (2005) Armin-design of a novel arm rehabilitation robot. In: Rehabilitation Robotics, 2005. ICORR 2005. 9th International Conference on. IEEE, pp 57–60

Perry JC, Rosen J, Burns S (2007) Upper-limb powered exoskeleton design. IEEE/ASME Trans Mechatron 12(4):408–417

Pirondini E, Coscia M, Marcheschi S, Roas G, Salsedo F, Frisoli A, Bergamasco M, Micera S (2016) Evaluation of the effects of the arm light exoskeleton on movement execution and muscle activities: a pilot study on healthy subjects. J Neuroeng Rehabil 13(1):9

Polygerinos P, Wang Z, Galloway KC, Wood RJ, Walsh CJ (2015) Soft robotic glove for combined assistance and at-home rehabilitation. Robot Auton Syst 73:135–143

Pons JL (2008) Wearable robots: biomechatronic exoskeletons. Wiley, Chichester

Quintero HA, Farris RJ, Goldfarb M (2011) Control and implementation of a powered lower limb orthosis to aid walking in paraplegic individuals. In: Rehabilitation Robotics (ICORR), 2011 IEEE International Conference on. IEEE, pp 1–6

Raspopovic S, Capogrosso M, Petrini FM, Bonizzato M, Rigosa J, Di Pino G, Carpaneto J, Controzzi M, Boretius T, Fernandez E et al (2014) Restoring natural sensory feedback in real-time bidirectional hand prostheses. Sci Transl Med 6(222):222ra19

Rea R, Beck C, Rovekamp R, Neuhaus P, Diftler M (2013) X1: a robotic exoskeleton for in-space countermeasures and dynamometry. In: AIAA SPACE 2013 Conference and Exposition, p 5510

Ruffaldi E, Barsotti M, Leonardis D, Bassani G, Frisoli A, Bergamasco M (2014) Evaluating virtual embodiment with the alex exoskeleton. In: International Conference on Human Haptic Sensing and Touch Enabled Computer Applications. Springer, pp 133–140

Sanchez R, Wolbrecht E, Smith R, Liu J, Rao S, Cramer S, Rahman T, Bobrow J, Reinkensmeyer D (2005) A pneumatic robot for re-training arm movement after stroke: rationale and mechanical design. In: Rehabilitation Robotics, 2005. ICORR 2005. 9th International Conference on. IEEE, pp 500–504

Sarac M, Solazzi M, Sotgiu E, Bergamasco M, Frisoli A (2017) Design and kinematic optimization of a novel underactuated robotic hand exoskeleton. Meccanica 52(3):749–761

Strausser KA, Kazerooni H (2011) The development and testing of a human machine interface for a mobile medical exoskeleton. In: Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on. IEEE, pp 4911–4916

Tropea P, Mazzoni A, Micera S, Corbo M (2017) Giuliano vanghetti and the innovation of cineplastic operations. Neurology 89(15):1627–1632

van der Kooij H, van Asseldonk EHF, Vlutters M. (2017) Towards Exoskeletons with Balance Capacities. In: González-Vargas J, Ibáñez J, Contreras-Vidal J., van der Kooij H, Pons J. (eds) Wearable Robotics: Challenges and Trends. Biosystems and Biorobotics, vol 16. Springer, Cham

Veneman JF, Kruidhof R, Hekman EE, Ekkelenkamp R, Van Asseldonk EH, Van Der Kooij H (2007) Design and evaluation of the lopes exoskeleton robot for interactive gait rehabilitation. IEEE Trans Neural Syst Rehabil Eng 15(3):379–386

Vertechy R, Frisoli A, Dettori A, Solazzi M, Bergamasco M (2009) Development of a new exoskeleton for upper limb rehabilitation. In: Rehabilitation Robotics, 2009. ICORR 2009. IEEE International Conference on. IEEE, pp 188–193

Wehner M, Quinlivan B, Aubin PM, Martinez-Villalpando E, Baumann M, Stirling L, Holt K, Wood R, Walsh C (2013) A lightweight soft exosuit for gait assistance. In: Robotics and Automation (ICRA), 2013 IEEE International Conference on. IEEE, pp 3362–3369

Zollo L, Roccella S, Guglielmelli E, Carrozza MC, Dario P (2007) Biomechatronic design and control of an anthropomorphic artificial hand for prosthetic and robotic applications. IEEE/ASME Trans Mechatron 12(4):418–429

Zoss AB, Kazerooni H, Chu A (2006) Biomechanical design of the berkeley lower extremity exoskeleton (bleex). IEEE/ASME Trans Mechatron 11(2):128–138

Zuo KJ, Olson JL (2014) The evolution of functional hand replacement: from iron prostheses to hand transplantation. Plast Surg 22(1):44–51