Wearable Robots: Biomechatronic Exoskeletons

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John Wiley & Sons, Ltd

Wearable Robots

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Foreword

Being a multidisciplinary area involving subjects such as mechanics, electronics and computing, the evolution and spread of robotics to different application sectors still requires intense interaction with other fields of science and technology. This applies equally when dealing with wearable robots, meaning robotic systems that a person wears to enhance his/her capabilities in some way. Since the first wearable robots, conceived in the early 1990s as amplifiers of human force or reach, progress in all robotics-related areas has been moving in the direction of a symbiosis between humans and robots as a means of enhancing human abilities in the fields of perception, manipulation, walking and so on.

Although the number of books available on robotics is huge, the existing literature in specific fields of robotic application is not so extensive; moreover, it appears that there is no book conceived as a compendium of all the subject matter involved in such specific emerging areas. The present book is intended to fill the gap in the field of wearable robots – an emerging sector that constitutes a step forward in robotic systems, which rely on the fact of having a human in the loop. That progress in the field is continuously expanding is evident from the number of publications on advances in research and development, new prototypes and even commercial products. Therefore, a book that brings together all the different subject matter encompassed by this discipline will assuredly be of valuable assistance in gaining an appreciation of the wide range of knowledge required; furthermore, by identifying the main concepts involved in dealing with such robots, it can be of help to new researchers wishing to enter the field.

As this book shows, in the field of wearable robots human/robot interaction is a key issue, from a physical or a cognitive point of view, or from both. Therefore, besides a solid knowledge of robotic techniques, research and development in this area also requires some background in anatomical behaviour of the human body and in the human neurological and cognitive systems. In this context, bioinspired or biomimetic design is of special importance for purposes of reproducing human functions or copying human actions respectively. Wearable robots must be designed to cope with specific working conditions, such as the need to accommodate a nonfixed structure, i.e. the human body; to be compliant, light and intrinsically safe enough to be worn by a user; or to be equipped with the requisite interfaces to enable easy intuitive control by a human.

Within this context, before going on to deal with exoskeletons – in the form of upper or lower limbs, or the trunk – as orthotic/prosthetic elements, the book looks at bioinspired and biomimetic systems, describing the human neuromotor system, the body kinematics and dynamics, and the human–machine interface requirements. The biologically inspired design of wearable robots requires a study of computational counterparts, such as genetic algorithms, as well as other technical issues like lightness of components, power efficiency, and general technological aspects of the elements involved in the design. On the subject of design of robot architectures for wearable robots, the book presents a preliminary study of human biomechanics and human mobility modelling. Special emphasis is placed on the analysis of potential human–machine interfaces for such robots, distinguishing between cognitive and physical interaction, which require quite different technologies: in the former case these have more to do with medical and biological aspects such as EEG and EMG signals, while in the latter case there is more reliance on engineering. Given the large number of sensors and actuators embedded in wearable robots, and also robot design requirements, communication networks are a key issue, which is dealt with by analysing the various existing techniques, naturally with particular attention to the performance of wireless technology.

With so broad a scope, the book will be of interest to students and researchers having some background in robotics and an interest or some experience in rehabilitation robots and assistive technology. It is also intended to provide basic educational material with which to introduce medical personnel or other specialists to the capabilities of such robotic systems. Rather than being a collection of materials, the book is carefully structured in such a way that the consecutive chapters allow the reader to perceive the context and requirements and gain an idea of the current solutions and future trends in this exciting field.

Alicia Casals
Professor, UPC

Preface

This book is the result of several years of research and work by the Bioengineering Group (CSIC) on the use of Robotics to assist handicapped people. The aim of the book is to provide a comprehensive discussion of the field of Wearable Robotics. Rehabilitation, Assistance and Functional Compensation are not the only fields of application for Wearable Robotics, but they may be regarded as paradigmatic scenarios for robots of this kind. The book covers most of the scientific topics relating to Wearable Robotics, with particular focus on bioinspiration, biomechatronic design, cognitive and physical human–robot interaction, wearable robot technologies (including communication networks), kinematics, dynamics and control. The book was enriched by the contribution of outstanding scientists and experts in the different topics addressed here. I would like to thank them all.

This book could not have been written without help and contributions from many people. I wish to express my gratitude to M. Wisse for his contributions to Chapter 2, particularly in all those aspects relating to the bioinspired design of robots, and to A. Schiele, also of Delft University of Technology (The Netherlands), for his contributions to Chapters 3 and 5; his comments in the field of kinematics, ergonomics and human–robot physical interaction are particularly interesting.

Many research groups worldwide have contributed by means of case studies. J.M. Belda-Lois, R. Poveda, R. Barberà, J.M. Baydal-Bertomeu, D. Garrido, F. Moll, M.J. Vivas and J.M. Prat, of the Instituto de Biomecánica de Valencia (Spain), provided valuable contributions in the fields of biomechanics, bioinspired design of exoskeletons and kinematic compatibility, as well as microclimate sensing, comfort and ergonomics in orthotics in Chapters 3, 5 and 6.

J.M. Carmena, of the Department of Electrical Engineering and Computer Sciences, Helen-Wills Neuroscience Institute, University of California (USA), contributed to Chapter 4 with new concepts for the cortical control of robots. In the same field but with the help of surface EEG, T.F. Bastos-Filho, M. Sarcinelli-Filho, A. Ferreira, W.C. Celeste, R.L. Silva, V.R. Martins, D.C. Cavalieri, P.N.S. Filgueira and I.B. Arantes, of the Federal University of Espirito Santo (Brazil), provided a discussion of brain-controlled robots and introduced some preliminary results with healthy users as a first step towards clinical validation of these technologies.

The book also reflects Italy's place at the forefront of Robotics research. Several groups contributed to this book. L. Beccai, S. Micera, C. Cipriani, J. Carpaneto, M.C. Carrozza, S. Roccella, E. Cattin, N. Vitiello and F. Vecchi, of the ARTS Lab, Scuola Superiore Sant'Anna, Pisa (Italy), enriched it with contributions in the field of bioinspired and biomechatronic design of wearable robots, in particular in upper limb exoskeletons for neuromotor research and in novel neuroprosthetic control of upper limb robotic prostheses. I would like to thank in particular M.C. Carrozza and Prof. P. Dario for their support. E. Farella and L. Benini, of the Department of Electronics, Computer Science and Systems, University of Bologna (Italy), contributed to the area of wireless sensor networks and the implementation of the posture and gesture interaction scheme. Finally, N.G. Tsagarakis and D.G. Caldwell, of the Italian Institute of Technology, in cooperation with S. Kousidou, of the Centre of Robotics and Automation, University of Salford (UK), contributed to the field of upper limb exoskeletons in those aspects relating to soft arm design and control.

There are also five additional contributions by groups from Finland, the USA, Iceland and Japan. J. Vanhala, of the Tampere University of Technology, contributed a discussion on wearable technologies with applications both to wearable robots and to smart textiles. J.C. Perry and J. Rosen, of the Department of Electrical Engineering, University of Washington (USA), provided a thorough discussion of upper limb exoskeletons with particular emphasis on kinematic compatibility between the human limb and the robot kinematics, from the special perspective of fitting into activities of daily living. D.P. Ferris, of the Division of Kinesiology, Department of Biomedical Engineering and Department of Physical Medicine and Rehabilitation, The University of Michigan (USA), presented a discussion on the application of pneumatic actuators to lower limb orthoses. K. De Roy, of Össur (Iceland), contributed a discussion on walking dynamics under normal, impaired and restored conditions following the fitting of robotic lower limb prostheses. I would like to thank F. Thorsteinsson for supporting this project and for our collaboration during the last few years. Finally, a full–body exoskeleton with pneumatic actuation is presented by K. Yamamoto, of the Kanagawa Institute of Technology (Japan).

Most of the work presented in this book has been developed in the framework of four European projects. Therefore, I would like to acknowledge the European Commission for the partial funding of this work under the following contracts:

- MANUS – modular anthropomorphous user-adaptable hand prosthesis with enhanced mobility and force feedback (EU Telematics DE-4205).
- DRIFTS – dynamically responsive intervention for tremor suppression (EU Quality of Life QLRT-2001-00536).
- GAIT – intelligent knee and ankle orthosis for biomechanical evaluation and functional compensation of joint disorders (UE IST IST-2001-37751).
- ESBiRRo – biomimetic actuation, sensing and control technology for limit cycle bipedal walkers (UE FP6-2005-IST-61-045301-STP).

In writing this book I have received the unstinting support of my colleagues in the Bioengineering Group. Professor R. Ceres and Dr L. Calderón contributed to the introduction to *Wearable Robotics* and to the concluding remarks and the outlook. Dr E. Rocon and A.F. Ruiz have been behind the contributions on physical human–robot interaction and on upper limb wearable robots, and R. Raya cooperated with them on the interaction between humans and robots. Dr A. Forner-Cordero contributed in those topics relating to the biological basis and in the biomechanical foundations for the design of wearable robots. In this particular regard, E. Turowska provided input on the kinematic analysis of both robot and human limbs.

The analysis of the cognitive interaction between humans and robots comes from L. Bueno, F. Brunetti and A. Frizera. L. Bueno contributed, in cooperation with J.C. Moreno, to the discussion on wearable robot technologies. In addition, J.C. Moreno provided the discussions on lower limb wearable robots. The main contribution from F. Brunetti was in the area of communication networks for wearable robots and wearable technologies.

Finally, I would like to thank all my colleagues in the Bioengineering Group, CSIC, in particular Luis and Lola, my family and my parents to whom I owe everything, and to God.

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1

Introduction to wearable robotics

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1.1 WEARABLE ROBOTS AND EXOSKELETONS

The history of robotics is one of ever closer interaction with the human actor. Originally, robots were only intended for use in industrial environments to replace humans in tedious and repetitive tasks and tasks requiring precision, but the current scenario is one of transition towards increasing interaction with the human operator. This means that interaction with humans is expanding from a mere exchange of information (in teleoperation tasks) and service robotics to a close interaction involving physical and cognitive modalities.

It is in this context that the concept of *Wearable Robots* (WRs) has emerged. Wearable robots are person-oriented robots. They can be defined as those worn by human operators, whether to supplement the function of a limb or to replace it completely. Wearable robots may operate alongside human limbs, as in the case of orthotic robots or exoskeletons, or they may substitute for missing limbs, for instance following an amputation. Wearability does not necessarily imply that the robot is ambulatory, portable or autonomous. Where wearable robots are nonambulatory, this is in most instances a consequence of the lack of enabling technologies, in particular actuators and energy sources.

A wearable robot can be seen as a technology that extends, complements, substitutes or enhances human function and capability or empowers or replaces (a part of) the human limb where it is worn. A possible classification of wearable robots takes into account the function they perform in cooperation with the human actor. Thus, the following are instances of wearable robots:

- *Empowering robotic exoskeletons*. These were originally called *extenders* (Kazerooni, 1990) and were defined as a class of robots that extends the strength of the human hand beyond its natural ability while maintaining human control of the robot. A specific and singular aspect of extenders is that the exoskeleton structure maps on to the human actor's anatomy. Where the extension of the ability of the human operator's upper limb is more to do with reach than power, master–slave robot configurations occur, generally in teleoperation scenarios.

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Figure 1.1 Wearable robots: (top left) an upper limb orthotic exoskeleton; (top right) an upper limb prosthetic robot; (bottom left) a lower limb orthotic exoskeleton; (bottom right) a lower limb prosthetic robot

- *Orthotic robots*. An orthosis is a mechanical structure that maps on to the anatomy of the human limb. Its purpose is to restore lost or weak functions, e.g. following a disease or a neurological condition, to their natural levels. The robotic counterparts of orthoses are robotic exoskeletons. In this case, the function of the exoskeleton is to complement the ability of the human limb and restore the handicapped function (see Figure 1.1).
- *Prosthetic robots*. A prosthesis is an electromechanical device that substitutes for lost limbs after amputation. The robotic counterparts of prostheses take the form of electromechanical wearable robotic limbs and make it possible to replace the lost limb function in a way that is closer to the natural human function. This is achieved by intelligent use of robotics technologies in terms of human–robot interaction (comprising sensing and control) and actuation (see Figure 1.1).

1.1.1 Dual human–robot interaction in wearable robotics

The key distinctive aspect in wearable robots is their intrinsic dual cognitive and physical interaction with humans. On the one hand, the key role of a robot in a *physical human–robot interaction* (pHRI) is the generation of supplementary forces to empower and overcome human physical limits (Alami *et al.*, 2006), be they natural or the result of a disease or trauma. This involves a net flux of power between both actors. On the other hand, one of the crucial roles of a *cognitive human–robot interaction* (cHRI) is to make the human aware of the possibilities of the robot while allowing him to maintain control of the robot at all times. Here, the term *cognitive* alludes to the close relationship between cognition – as the process comprising high-level functions carried out by the human brain, including comprehension and use of speech, visual perception and construction, the ability to calculate, attention (information processing), memory and executive functions such as planning, problem-solving, self-monitoring and perception – and motor control.

Both pHRI and cHRI are supported by a *human–robot interface* (HRi). An interface is a hardware and software link that connects two dissimilar systems, e.g. robot and human. Two devices are said to be interfaced when their operations are linked informationally, mechanically or electronically. In the context of wearable robotics, the interface is the link that supports interaction – the interaction between robot and human through control of the flow of information or power.

In wearable robotics, a *cognitive human–robot interface* (cHRi) is explicitly developed to support the flow of information in the cognitive interaction (possibly two-way) between the robot and the human. Information is the result of processing, manipulating and organizing of data, and so the cHRi in the human-robot direction is based on data acquired by a set of sensors to measure bioelectrical and biomechanical variables. Likewise, the cHRi in the robot–human direction may be based on biomechanical variables, a subset of bioelectrical variables, e.g. electroneurography (ENG), and modalities of natural perception, e.g. visual and auditory.

Similarly, a *physical human–robot interface* (pHRi) is explicitly developed to support the flow of power between the two actors. The pHRi is based on a set of actuators and a rigid structure that is used to transmit forces to the human musculoskeletal system. The close physical interaction through this interface imposes strict requirements on wearable robots as regards safety and dependability.

Cognitive and physical interactions are not independent. On the one hand, a perceptual cognitive process in the human can be triggered by physical interaction with the robot. One example is a wearable robot physically interacting with an operator to render haptic information on a virtual or remote object, so that the operator can feel the object (soft or rigid) (see Figure 1.2).

On the other hand, the cognitive interaction can be used to modify the physical interaction between human and robot, for instance to alter the compliance of an exoskeleton. One example is tremor suppression based on exoskeleton–human interaction: the onset of a tremor can be inferred from the biomechanical data of limb motion (cognitive process); this is used to modify the biomechanical characteristics of the human limb (damping and apparent inertia), which in turn leads to tremor reduction.

In this context, the cognitive interaction resulting from a human–robot (H–R) physical interaction can be either *conscious* or *involuntary*. The previous example of haptic rendering by means of wearable robots is a good example of conscious perceptual cognitive interaction. Involuntary cognitive interaction is produced by low-level, reflex-like mechanisms on either side of the human–robot interface. This is exemplified by a more subtle case of physically triggered human involuntary cognitive processes experienced in exoskeletons used to suppress tremor of the human upper limb. It has been shown (Manto *et al.*, 2007) that the modification of biomechanical characteristics of the human musculoskeletal system around a joint, e.g. the wrist, triggers a modification of human motor control processes that results in migration of tremor to adjacent joints, e.g. the elbow.

Involuntary cognitive interactions between robot and human can of course be nested at different levels. In the previous example of tremor reduction by means of exoskeletons, it was found that

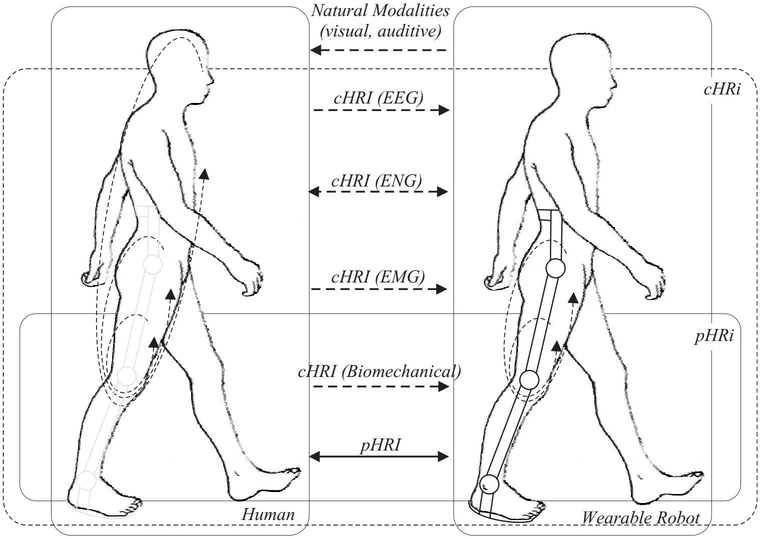

Figure 1.2 Schematic representation of dual cognitive and physical interaction in wearable robots

visual feedback of tremor reduction to the user – i.e. the use of natural perceptual visual information – triggers human motor control mechanisms that further reduce tremor. These human motor control mechanisms operate on the human side of the interface and are superimposed on the tremor migration mechanisms of the previous example; they are triggered by the pHRI and the cHRI though natural modes of perception (vision) and involve different motor control levels.

1.1.2 A historical note

Of the different wearable robots, exoskeletons are the ones in which the cognitive (information) and physical (power) interactions with the human operator are most intense. Scientific and technological work on exoskeletons began in the early 1960s. The US Department of Defense became interested in developing the concept of a powered 'suit of armor'. At the same time, at Cornel Aeronautical Laboratories work started to develop the concept of man–amplifiers – manipulators to enhance the strength of a human operator. The existing technological limitations on development of the concept were established in 1962; these related to servos, sensors and mechanical structure and design. Later on, in 1964, the hydraulic actuator technology was identified as an additional limiting factor.

General Electric Co. further developed the concept of human–amplifiers through the *Hardiman project* from 1966 to 1971. The Hardiman concept was more of a robotic master–slave configuration in which two overlapping exoskeletons were implemented. The inner one was set to follow human motion while the outer one implemented a hydraulically powered version of the motion performed by the inner exoskeleton. The concept of extenders versus master/slave robots as systems exhibiting genuine information and power transmission between the two actors was coined in 1990 (Kazerooni, 1990).

Efforts in the defence and military arena have continued up to the present, chiefly promoted by the US Defense Advanced Research Projects Agency (DARPA). Additional details on this can be found in Section 1.4.

Rehabilitation and functional compensation exoskeletons are another classic field of application for wearable robotics. Passive orthotic or prosthetic devices do not fall within the scope of this book, but they may be regarded as the forebears of current rehabilitation exoskeletons. More than a century ago, Prof. H. Wangenstein proposed the concept of a mobility assistant for scientists bereft of the use of their legs:

> This amazing feat shall revolutionize the way in which paraplegic Scientists continue their honorable work in the advancement of Science! Even in this modern day and age, some injuries cannot be healed. Even with all the Science at our command, some of our learned brethren today are without the use of their legs. This Device will change all that. From an ordinary-appearing wheelchair, the Pneumatic Bodyframe will transform into a light exoskeleton which will allow the Scientist to walk about normally. Even running and jumping are not beyond its capabilities, all controlled by the power of the user's mind. The user simply seats himself in the chair, fits the restraining belts around his chest, waist, thighs and calves, fastens the Neuro-Impulse Recognition Electrodes (N.I.R.E.) to his temples, and is ready to go!

The concept introduced by Prof. Wangenstein in 1883 contains the main features of current state-of-the-art wearable robotic exoskeletons: a pneumatically actuated body frame (in the form of a light exoskeleton), mapping on to the human lower limb, in which a cHRI is established by means of brain activity electrodes (known as NIRE).

Among the spinoff applications of robotic extenders are robotic upper limb orthoses (Rabischong, 1982). Although studies on active controlled orthoses date back to the mid 1950s (Battyke, Nightingale and Whilles, 1956), the first active implementations of powered orthoses were the work of Rahman *et al.* (2000). This functional upper limb orthosis was conceived for people with limited strength in their arms.

1.1.3 Exoskeletons: an instance of wearable robots

The exoskeleton is a species of wearable robot. The distinctive, specific and singular aspect of exoskeletons is that the exoskeleton's kinematic chain maps on to the human limb anatomy. There is a one-to-one correspondence between human anatomical joints and the robot's joints or sets of joints. This kinematic compliance is a key aspect in achieving ergonomic human–robot interfaces, as further illustrated in Chapters 3 and 5.

In exoskeletons, there is an effective transfer of power between the human and the robot. Humans and exoskeletons are in close physical interaction. This is the reverse of master–slave configurations, where there is no physical contact between the slave and the human operator, which are remote from one another. However, in some instances of teleoperation, an upper limb exoskeleton can be used as the interface between the human and the remote robot. According to this concept, the exoskeleton can be used as an input device (by establishing a pose correspondence between the human and the slave or remote manipulator), as a force feedback device (by providing haptic interaction between the slave robot and its environment), or both.

The interaction between the exoskeleton and the human limb can be achieved through *internal force* or *external force* systems. Which of these force interaction concepts is chosen depends chiefly on the application. On the one hand, empowering exoskeletons must be based on the concept of external force systems; empowering exoskeletons are used to multiply the force that a human wearer can withstand, and therefore the force that the environment exerts on the exoskeleton must be grounded: i.e. in external force systems the exoskeleton's mechanical structure acts as a load-carrying device and only a small part of the force is exerted on the wearer. The power is transmitted to an external base, be it fixed or portable with the operator. The only power transmission is between the human limbs and the robot as a means of implementing control inputs and/or force feedback. This concept is illustrated in Figure 1.3 (right).

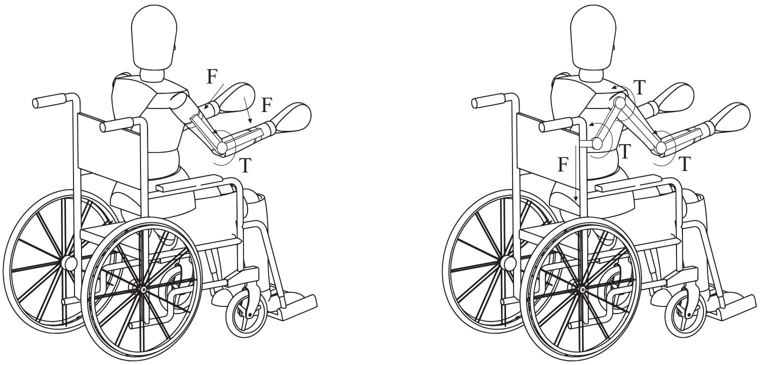

Figure 1.3 Schematic representation of internal force (left) and external force (right) exoskeletal systems

On the other hand, orthotic exoskeletons, i.e. exoskeletons for functional compensation of human limbs, work on the internal force principle. In this instance of a wearable robot, the force and power are transmitted by means of the exoskeleton between segments of the human limb. Orthotic exoskeletons are applicable whenever there is weakness or loss of human limb function. In such a scenario, the exoskeleton complements or replaces the function of the human musculoskeletal system. In internal force exoskeletons, the force is nongrounded; force is applied only between the exoskeleton and the limb. The concept of internal force exoskeletons is illustrated in Figure 1.3 (left).

Superimposing a robot on a human limb, as in the case of exoskeletons, is a difficult problem. Ideally, the human must feel no restriction to his/her natural motion patterns. Therefore, kinematics plays a key role in wearable exoskeletons: if robots and humans are not kinematically compliant, a source of nonergonomic interaction forces appears. This is comprehensively addressed in Sections 3.4 and 5.2. The former analyses the kinematics of interacting human–robot systems. The latter theoretically analyses the forces resulting from kinematically noncompliant human–robot systems; this theoretical analysis is then quantified in Case Study 5.5.

Kinematic compatibility is of paramount importance in robotic exoskeletons working on the principle of internal forces. The typical misalignment between exoskeleton and anatomical joints results in uncomfortable interaction forces where both systems are attached to each other. Given the complex kinematics of most human anatomical joints, this problem is hard to avoid. The issue of compliant kinematics calls for bioinspired design of wearable robots and imposes a strong need for control of the human–robot physical interaction.

Exoskeletons are also characterized by a close cognitive interaction with the wearer. This cHRI is in most instances supported by the physical interface. By means of this cognitive interaction, the human commands and controls the robot, and in turn the robot includes the human in the control loop and provides information on the tasks, either by means of a force reflexion mechanism or of some other kind of information.

1.2 THE ROLE OF BIOINSPIRATION AND BIOMECHATRONICS IN WEARABLE ROBOTS

It is widely recognized that evolutionary biological processes lead to efficient behavioural and motor mechanisms. Evolution in biology involves all aspects and functions of creatures, from perception to actuation–locomotion, in particular gait, and manipulation–through efficient organization of motor control. Evolution is a process whereby functional aspects of living creatures are optimized. This optimization process seeks the maximization of certain objective functions, e.g. manipulative dexterity in human hands and efficiency in terms of energy balance in performing a certain function. Chapter 2 of this book analyses the basis for bioinspiration and biomimetism in the design of wearable robots.

Neurobiology plays a crucial role in hypothesizing engineering-inspired biological models. For example, some biological models explain how energetically efficient locomotion and gait speed modulation of six-legged insects can be achieved through frequency and stride length modification resulting in effective speed change. Engineering in turn plays a crucial role in validating neurobiological models by looking at how artificial systems reproduce and explain biological behaviour and performance. For instance, parallax motion in insects is validated by means of Dro-o-boT, a robot whose motion proved identical to that of insects when programmed following the principle of parallax motion (Abbott, 2007).

It is clear that the design of wearable robots can benefit from biological models in a number of aspects like control, sensing and actuation. Likewise, wearable robots can be used to understand and formalize models of biological motor control in humans. This concurrent view calls for a multidisciplinary approach to wearable robot development, which is where the concept of *biomechatronics* comes in.

The term *mechatronics* was coined in Japan in the mid 1970s and has been defined as the engineering discipline dealing with the study, analysis, design and implementation of hybrid systems comprising mechanical, electrical and control (intelligence) components or subsystems (Pons, 2005). Mechatronic systems closely linked to biological systems have been referred to as *biocybernetic systems* in the context of electromyography (EMG) control of the full-body HAL-5 exoskeleton wearable robot system (see Case Study 9.4). The concept of *biomechatronics* is not limited to biocybernetic systems.

Biomechatronics can be analysed by analogy to biological systems integrating a musculoskeletal apparatus with a nervous system (Dario *et al.*, 2005). Following this analogy (see Figure 1.4), biomechatronic systems integrate mechanisms, embedded control and human–machine interaction (HMI), sensors, actuators and energy supply in such a way that each of these components, and the whole mechatronic system, is inspired by biological models. This book stresses the biomechatronic conception of wearable robots:

- Bioinspiration is analysed in Chapter 2. This chapter explains the essentials of the design of wearable robots based on biological models.
- Mechanisms (in the context of wearable robots) are analysed in Chapter 3. This chapter addresses the particular kinematic and dynamic considerations of mapping robots on to human limb anatomy.
- HMI in the context of wearable robots, i.e. human–robot interaction, is analysed in Chapters 4 and 5. The former focuses on the cognitive aspects of this interaction while the latter addresses the physical interaction.
- Sensors, actuators and energy supply–i.e. technologies enabling the implementation of wearable robots–are analysed in Chapter 6. In many instances, sensors, actuators and control components are included in the wearable robot structure as nodes of a communication network. Networks for WRs are analysed in Chapter 7.

Biomechatronics may in a sense be viewed as a scientific and engineering discipline whose goal is to explain biological behaviour by means of artificial models, e.g. the system's components: sensors, actuators, control etc. This is consistent with the dual role of bioinspiration: firstly, to gain insight by observing biological models and, secondly, to explain biological function by means of engineering models.

Biomechatronics may be regarded as an extension of mechatronics. The scope of biomechatronics is broader in three distinctive aspects: firstly, biomechatronics intrinsically includes bioinspiration

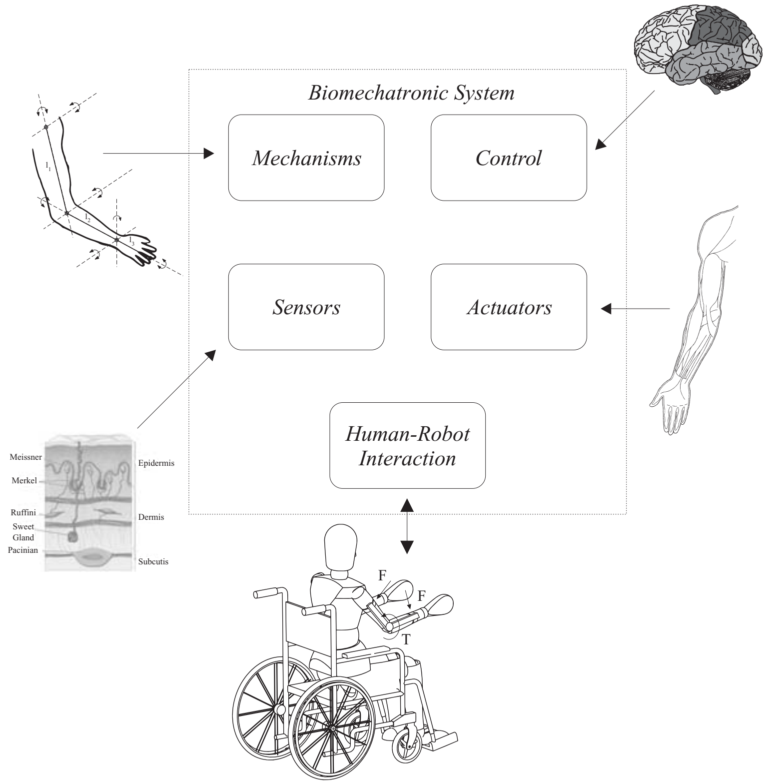

Figure 1.4 Components in a biomechatronic system

in the development of mechatronic systems, e.g. the development of bioinspired mechatronic components (control architectures, actuators, etc.); secondly, biomechatronics deals with mechatronic systems in close interaction with biological systems, e.g. a wearable robot interacting cognitively and physically with a human; and, finally, biomechatronics commonly adopts biologically inspired design and optimization procedures in the development of mechatronic systems, e.g. the adoption of genetic algorithms in the optimization of mechatronic components or systems. These three salient aspects of biomechatronics are further illustrated in the following paragraphs.

1.2.1 Bioinspiration in the design of biomechatronic wearable robots

Bioinspiration has been extensively adopted in the development of wearable robots. This includes the development of the complete robot system and its components. Bioinspiration in the context of actuator design has been studied in detail elsewhere (Pons, 2005). Here, a few examples are cited in the context of wearable robots, which are further detailed in case studies throughout this book.

Bioinspired actuators have also been developed in the context of wearable robots. A bioinspired knee actuator for a lower limb exoskeleton is analysed in Case Study 6.7. This shows that due to power and torque requirements in human gait, no state-of-the-art actuator technology can be applied to compensate quadriceps weakness during gait. It can be shown that the mechanical equivalent of the quadriceps muscle during the stance phase is a rigid spring–damper configuration and the mechanical