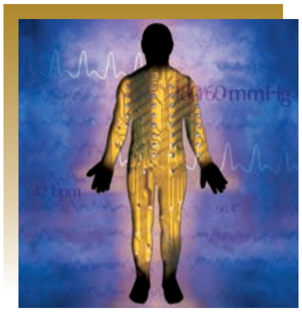

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# Wearable Sensors/Systems and Their Impact on Biomedical Engineering

*An Overview from the Guest Editor*

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Recent advances in miniature devices, as well as mobile and ubiquitous computing, have fostered a dramatic growth of interest for wearable technology. Wearable sensors and systems have evolved to the point that they can be considered ready for clinical application. This is due not only to the tremendous increase in research efforts devoted to this area in the past few years but also to the large number of companies that have recently started investing aggressively in the development of wearable products for clinical applications. Stable trends showing a growth in the use of this technology suggest that soon wearable systems will be part of routine clinical evaluations.

The interest for wearable systems originates from the need for monitoring patients over extensive periods of time. This case arises when physicians want to monitor individuals whose chronic condition includes risk of sudden acute events or individuals for whom interventions need to be assessed in the home and outdoor environment. If observations over one or two days are satisfactory, ambulatory systems can be utilized to gather physiological data. An obvious example is the use of ambulatory systems for ECG monitoring, which has been part of the routine evaluation of cardiovascular patients for almost three decades. However, ambulatory systems are not suitable when monitoring has to be accomplished over periods of several weeks or months, as is desirable in a number of clinical applications.

Wearable systems are totally nonobtrusive devices that allow physicians to overcome the limitations of ambulatory technology and provide a response to the need for monitoring individuals over weeks or even months. They typically rely on wireless, miniature sensors enclosed in patches or bandages, or in items that can be worn, such as a ring or a shirt. They take advantage of hand-held units to temporarily store physiological data and then periodically upload that data to a database server via a wireless LAN or a cradle that allow Internet connection. The data sets recorded using these systems are then processed to detect events predictive of possible worsening of the patient's clinical situation or they are explored to assess the impact of clinical interventions.

All these aspects of wearable technology are covered by this special issue, which is introduced by four commentaries of physicians who share with the readership their vision on future clinical applications of wearable technology, thus pointing out its tremendous potential. Phil Binkley, M.D., professor of medicine at The Ohio State University Division of Cardiology, shares with us his vision on potential applications of wearable devices in cardiovascular research and clinical practice. Walter Frontera, M.D., Ph.D., chairman of the Department of Physical Medicine and Rehabilitation at Harvard Medical School, provides us with a clinician's viewpoint of the dramatic improvements in patient management that wearable devices could foster. David G. Standaert, M.D., Ph.D., associate professor of neurology, Harvard Medical School and associate neurologist at Massachusetts General Hospital, points out in his commentary the clinical relevance and potential outcomes of monitoring motor fluctuations in patients with Parkinson's disease. Finally, Joel Stein, M.D., director of the stroke program and chief medical officer at Spaulding Rehabilitation Hospital, highlights the need for monitoring poststroke hemiplegic patients in the home and outdoor environment in order to assess the impact of clinical interventions and plan more effective rehabilitation strategies.

The first five articles of this special issue are focused on the development of sensors and systems. In the first article, Asada et al. describe the evolution of the ring sensor over the past eight years. This is likely the most renowned project in the area of wearable devices. The result of several years of work is a pulse oximetry sensor that allows one to continuously monitor heart rate and oxygen saturation in a totally unobtrusive way. The device is shaped like a ring and thus it can be worn for long periods of time without any discomfort to the subject. The ring sensor is equipped with a low-power transceiver that accomplishes bidirectional communication with a base station, thus allowing one to reconfigure the sensor when necessary and to upload data at any point in time. In a nutshell, this is a "jewel" in the wearable technology arena.

The second article, by Park and Jayaraman, demonstrates the great impact on the clinical potential of wearable systems of the Georgia Tech Wearable Motherboard, the result of a revolutionary idea that allowed Dr. Jayaraman's team to develop a garment (i.e., a shirt) that actually functions as a wearable health monitoring system. This concept has been developed into a product that is now commercially available and allows one to record heart rate, body temperature, motion, position, barrier penetration, and the like in a totally nonencumbering manner. Park and Jayaraman point out a

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number of clinical challenges that can find a response in technological advances and they discuss future possible developments in wearable systems as well as the resulting transformation of healthcare and positive impact on the quality of life of individuals.

In the article that follows, Jovanov et al. present their approach to develop personal health monitors based on a wireless body area network of intelligent sensors. Body area networks of wireless intelligent sensors are linked to a personal server via a mobile gateway, i.e., a PDA-based device that allows easy access to standard wireless technology such as Bluetooth and IEEE 802.11b. With the proposed approach, several subjects can be monitored simultaneously by integrating individual wearable devices into a distributed wireless system. This is a key characteristic of the wireless system for the application presented in this article. In fact, the objective of the study is to evaluate responses to a stressful training situation in a group of individuals simultaneously involved in the experimental procedures. Data analysis is based on heart rate variability observations that correlate with the outcome of psychological tests and hormonal responses.

Winters et al. provide the readers with their vision of issues related to integrating wearable technology into neurorehabilitation and consumer-centered mobile telerehabilitation. Their approach is centered on the concept of intelligent telerehahabilitative assistants. These provide multimedia teleconferencing and wireless communication tools, means to perform collection of sensor data and user-based information associated with events to be monitored, and expert system modules implemented using neural networks and fuzzy logic that are set in place to manage events requiring immediate action. Connectivity to the Internet is provided by PDA-based devices and more generally by mobile computing tools relying on IEEE 802.11b (wLAN), Bluetooth (wPAN), and cell phone technology (wMAN). Applications of this approach to poststroke patients and individuals undergoing cardio-pulmonary rehabilitation, as well as other areas of rehabilitation, are suggested and modules to provide support to clinical decisions are discussed.

In the fifth article of this issue, Korhonen et al. discuss how wearable technology will be integrated in the home of the future. As opposed to focusing on sensors and measurement techniques, Korhonen and colleagues offer a view on the design of systems to monitor the health status of individuals in their home from a user's perspective, a data communication perspective, a software perspective, and from a system integration perspective. In order to demonstrate the proposed concept, the authors describe the wireless wellness monitor, a project in which their research team aims to develop a prototype for home supporting ubiquitous computing applications for wellness management and home automation.

The three subsequent articles have mainly a clinical slant on the topic of this special issue. In the first one, Elizabeth Waterhouse discusses how wearable technology could open new horizons in ambulatory electroencephalography (AEEG). The main application of AEEG is to establish the diagnosis of epilepsy and to aid in the confirmation of seizure control. Miniature systems make it feasible to monitor EEG data over extended periods with improved diagnostic and assessment capability. In addition, the development of fast processing algorithms that has marked this field in the recent past has made it possible to design systems that identify characteristics of the EEG recordings that are predictive of seizure events. Subjects can be alerted minutes to hours before a seizure occurs, which ideally allows them the time necessary to self-administer acute preventive treatment.

The second of the articles with clinical focus, by Kario et al., discusses the relevance of ambulatory blood pressure monitoring and potential improvements related to advances in miniature technology. Along with emphasizing the strong relationship between specific patterns shown by diurnal and nocturnal blood pressure behaviors and the risk of potentially lethal cardiovascular events, the authors present results from a study in which they combined ambulatory blood pressure monitoring with Holter ECG and actigraphy. This body of measures appears to provide tools that are valuable in risk stratification and planning preventive measures to minimize worsening of cardiovascular disorders.

Finally, Moy et al. discuss the use of wearable systems for monitoring patients with chronic obstructive pulmonary disease. The use of personal activity monitors in these patients appears to be extremely valuable because physical inactivity is an important variable in the dyspnea-inactivity deconditioning spiral commonly seen in these patients. It is important that physicians be provided with tools in order to plan an intervention when needed in order to avoid exercise intolerance. When patients become progressively homebound and socially isolated, this sequence of events frequently impairs the patient's health-related quality of life. Concomitantly, some individuals develop worsening depression and anxiety and may withdraw progressively from their usual routines. Wearable technology could provide a tremendous clinical tool for intervening when patients need support.

A third set of articles is devoted to the description of signal processing procedures designed to take full advantage of the dramatic amount of data gathered using wearable systems. The first of these papers, by Keijsers et al., focuses on the application of wearable technology to monitor dyskinesia in patients with Parkinson's disease. In the study, observations are performed during motor fluctuations related to levodopa intake. Accelerometers are used to measure patterns of movement, and an ambulatory system provides a means for storing the data that are later uploaded to another system for analysis. A neural-network-based approach is presented that allows one to match feature sets derived from the accelerometer data and clinical scores obtained by means of the unified Parkinson's Disease rating scale (UPDRS). The results show good correlation between the output of the trained neural network and clinical scores assigned by an expert physician who examined the patients and watched the experimental procedures.

The second article devoted to signal processing algorithms designed for the analysis of data gathered using wearable technology is by Akay et al. This research team proposes the use of the matching pursuit algorithm to analyze patterns of movement in poststroke hemiplegic patients. Akay and colleagues analyze patterns of acceleration signals recorded from both healthy individuals and poststroke hemiplegic subjects and demonstrate that characteristic patterns mark acceleration signals recorded from patients with different degrees of impairment. The results suggest that acceleration signals in severe poststroke hemiplegic patients are marked by a reduction in the energy of continuous patterns and an increase in the energy of burst patterns compared to healthy individuals. Patients with moderate and mild impairment appear to show characteristics that are intermediate between healthy control subjects and patients affected by a severe degree of impairment.

The next article is the result of a collaboration between my team at Harvard Medical School and Dr. Westgaard's team at Norwegian University of Science and Technology, Trondheim, Norway. The article aims at presenting a concept that we have pursued in the recent past; namely, the development of data mining techniques for the analysis of signals recorded using wearable technology. This approach is based on the acknowledgment that wearable technology allows one to record a dramatic amount of data, that little a priori information is available about the phenomena that we intend to observe in the real world, and that we therefore need to rely on methods capable of discovering information in these large data sets. In this article we propose the use of vector quantization and projection algorithms and the use of clustering techniques to detect subsets of data each associated with a specific condition.

The last and closing article of this special issue, by Manto et al., describes results of a cross-national multidisciplinary project, the dynamically responsive intervention for tremor suppression (DRIFTS), supported by the European Commission's Fifth Framework Programme. The project aims at creating proof-of-concept prototypes of wearable active orthoses for the suppression of upper limb tremor while preserving natural movement. Another major goal of the project is the development of a prototyping and evaluation platform for future elaboration of wearable ambulatory tremor suppression devices. The prototyping platform could be used to assess the efficacy of available sensing, actuating, and control technologies for tremor suppression. This study is part of what I see as a new "wave" in wearable technology in which miniature sensors and mobile computing are utilized to implement closed-loop systems; namely, orthoses and prostheses that adapt their modality of functioning to the needs of individuals.

This body of articles provides the reader with a good "picture" of the state-of-the-art in wearable technology. The four areas that I see as of paramount importance to understanding recent advances in wearable technology are all covered by the articles included in this special issue. These areas are: 1) wearable sensors, 2) wearable systems, 3) signal processing and analysis procedures, and 4) closed-loop systems for adaptive orthoses and prostheses.

I would like to thank all of the authors for contributing to this special issue with exciting reports of their current research activities toward the development of wearable systems. A special thanks goes to the reviewers for their careful work. Finally, I would like to express my gratitude to John Enderle, editor-in-chief, for supporting this initiative and for the enthusiasm and patience that he demonstrated during the preparation of the manuscripts published in this most significant issue on wearable sensors/systems and their impact on biomedical engineering.

**Paolo Bonato** received the M.S. degree in electrical engineering from Politecnico di Torino, Torino, Italy, in 1989 and the Ph.D. degree in biomedical engineering from Università di Roma "La Sapienza," Roma, Italy, in 1995. From 1990 to 1991 he was a research fellow with the Biophysics Research Group of IRST, Trento, Italy, where he was active in the field of signal processing applied to the cardiovascular system. In 1995 and 1996, he held a postdoctoral Fellowship at the Dipartimento di Elettronica of Politecnico di Torino, Torino, Italy. In 1996 he moved to the NeuroMuscular Research Center of Boston University, Boston, Massachusetts, as research assistant professor. Since 2002 he has been on the faculty of the Department of Physical Medicine and Rehabilitation, Harvard Medical School at Spaulding Rehabilitation Hospital, where he is the director of the Motion Analysis Laboratory. His principal research interests include signal processing applied to rehabilitation engineering, analysis of nonstationary signals by time-frequency analysis, electromyography applied to kinesiology, and biomechanics of movement. More recently, his focus has been on intelligent signal processing for investigating problems in neurophysiology and neuro-fuzzy inference systems for the analysis of data recorded using wearable sensors. Dr. Bonato is a Member of IEEE Engineering in Medicine and Biology Society and of the IEEE Signal Processing Society.

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