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Wearable Sensors and Systems

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Wearable Sensors and Systems

From Enabling Technology to Clinical Applications

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Over the past decade, wearable technology has gained the interest of researchers and clinicians [1]. The motivation for the development of wearable sensors and systems is due to the tremendous benefits that could be associated with long-term monitoring of individuals in the home and community settings. For example, in Figure 1, an individual affected by a balance disorder is monitored while at the gym or a clinical center (e.g., undergoing balance training). Here, exercise compliance and performance are monitored via motion sensors attached to the wrists and ankles: the interaction with a parallel-bar setup is captured by sensorized gloves that track hand movements, and physiological responses to the exercise are gathered using a chest strap that enables monitoring of heart rate and respiratory rate. The subject carries a cell phone in his/her pocket, which serves as data logger (i.e., the cell phone "talks" to the sensors positioned on the body) and as a gateway for remote access to the subject's data. Access to the subject's data is achieved via a cell phone network or via a wireless local area network. Data are then relayed via the Internet to emergency personnel (e.g., an ambulance service), a family member or caregiver, and clinical personnel (e.g., the subject's primary care physician) as needed to respond to emergency situations, assess the subject's status, and plan clinical interventions.

A Decade of Development of Wearable Technology

Interest in monitoring individuals in the home and community settings is not new and is in fact one of the factors that originated the field of telemedicine (recently renamed as *connected health* to emphasize the link between clinical personnel and patients that has been made possible by communication technologies such as the Internet). Researchers believe that long-term monitoring of physiological data could lead to significant improvements in the diagnosis and treatment of cardiovascular diseases [2]. It could, for instance, overcome shortcomings of currently available technology (e.g., Holter monitoring), such as the inability of capturing rarely occurring events of diagnostic relevance. Home monitoring of movement patterns in patients with motor disorders also could have a dramatic impact on the clinical management of impairing symptoms. For example, monitoring the severity of parkinsonian symptoms could facilitate medication titration as the disease progresses, thus minimizing impairments associated with severe dyskinesia, bradykinesia, rigidity, and akinesia. Researchers envisioned the potential benefits of field monitoring of patients with Parkinson's disease since the early 1990s [3], [4]. However, technological limitations prevented the immediate clinical application of the methodologies proposed.

Starting in the late 1990s, a tremendous effort has been made in the field of wearable technology toward closing the gap between vision and reality. Researchers have been engaged in developing technologies to enable the shared vision that long-term home monitoring could revolutionize the way medicine is practiced and have focused on
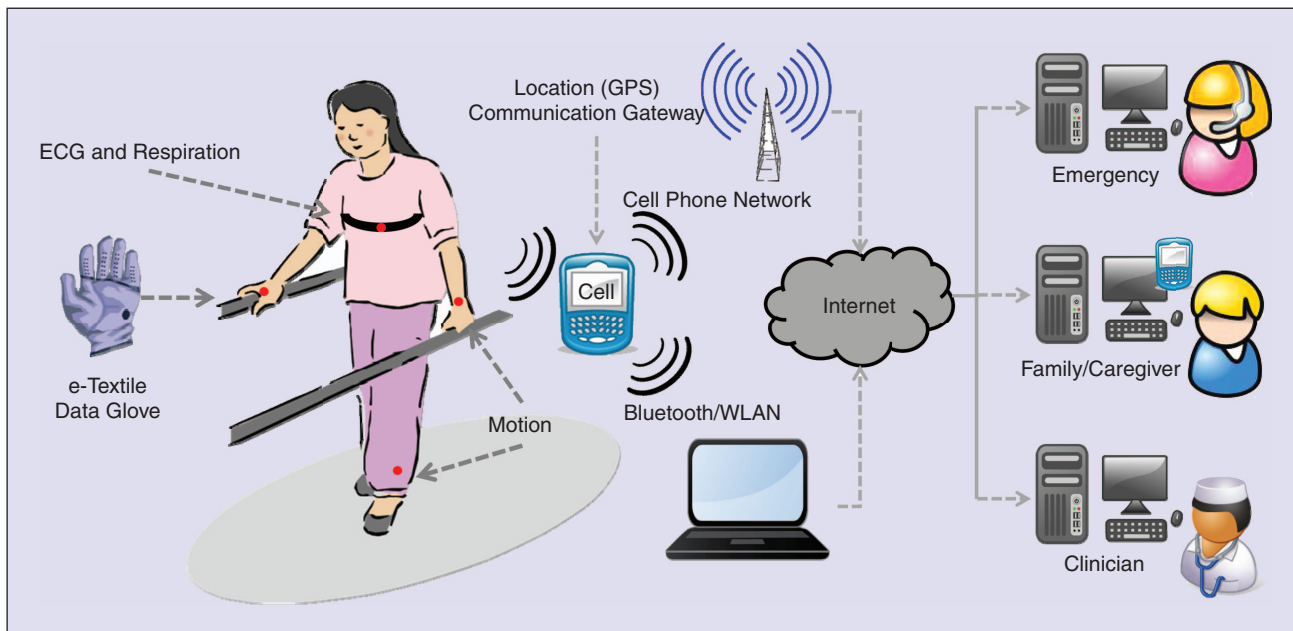
Fig. 1. Schematic representation of a system for patients' monitoring in the home and community settings. A subject is shown while exercising at the gym (e.g., undergoing balance therapy). Exercise compliance, exercise performance, and the associated physiological responses (i.e., heart rate and respiratory rate) are monitored via wearable sensors. A cell phone serves as a data logger and gateway for communication with a remote location via a cell phone network and/or the Internet.

two major approaches to implement wearable systems. These two distinct approaches leverage wireless technology and e-textile solutions, respectively [5]. It could be argued that this is purely a technology-based distinction and that future clinical systems will most likely combine wireless and e-textile technologies according to the requirements of the application at hand. However, hybrid systems integrating wireless and e-textile

Fig. 2. Schematic representation of a wearable system that allows one to collect movement and physiological data (i.e., heart rate and respiratory rate). Movement data are gathered using the four nodes equipped with accelerometers that are strapped around the ankles and wrists. Physiological data are collected via a chest strap.

technologies still appear to be a futuristic possibility. Research groups in the field of wearable technology are typically focused on one technology or the other, since the technical expertise necessary to develop systems leveraging both technologies (i.e., wireless and e-textile) are very different and rarely found in a single research group.

The development of wearable systems based on wireless technology leverages the miniaturization of sensors, availability of low-power radios, and development of dedicated operating systems (e.g., TinyOS) for small sensor units and networks of sensor units. Such networks are referred to as body sensor networks, and the sensor units are referred to as sensor nodes. A schematic representation of a body sensor network is shown in Figure 2. In the figure, a SHIMMER unit [6] is displayed as an example of a sensor node. A subject is depicted with sensor nodes attached to wrists and ankles, a setup suitable to monitor major motor activities. A chest strap is used to monitor heart rate and respiratory rate, thus capturing physiological responses to motor activities and potential cardiovascular problems that can be detected, for instance, via analysis of the heart rate and its variability. The nodes communicate with a base station (not shown in the figure) that could be either a data logger worn by the subject or a computer located in the environment surrounding the subject.

Advances in sensor technology have been essential to the implementation of body sensor networks. Researchers have put a great deal of effort on developing ways to unobtrusively monitor vital signs, with a particular emphasis on cardiac activity. Seminal work contributed by the group led by Asada and coworkers [7], [8] resulted in the ring sensor, a ring-shaped photoplethysmographic sensor capable of transmitting data wirelessly to a base station, which provides the ability to monitor heart rate and oxygen in the blood. More recently, Wang et al. [9] developed an earpiece photoplethysmographic sensor that has light-emitting diodes and photodiodes positioned
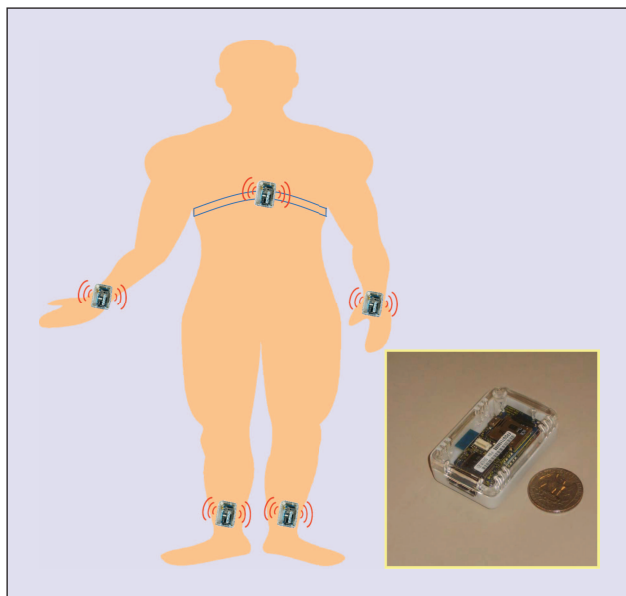
around the outer ear—as opposed to being attached to the earlobe as are commercially available photoplethysmographic sensors—thus leading to improved comfort. Also, Vogel et al. [10] developed an in-ear sensor suitable to record heart rate and, in the future, oxygen in the blood. Unobtrusive blood pressure monitoring has also been the focus of significant research efforts. Wristwatch type monitors, such as the MediWatch [11], were first developed by leveraging the miniaturization of sensors based on traditional approaches to measure blood pressure (i.e., via blood flow temporary obstruction). More recently, researchers have focused their work in this field on the pulse transit time technique [12], [13]. The technique leverages the relationship between blood pressure and the time between the R-peak of the electrocardiogram and a peak identified on the photoplethysmogram. Furthermore, researchers interested in tracking patients' movement patterns have been relying on the advances that have marked the field of microelectromechanical systems over the past two decades. Thanks to the progress in this field, sensors like accelerometers, gyroscopes, and magnetometers are now available that meet the requirements (e.g., low power consumption) for use as part of a body sensor network. Using this technology, researchers and clinicians can currently monitor subjects' movement patterns and possibly even reconstruct movement trajectories [14]. Advances in sensor technology have been combined with progress in short-range communication technologies such as ultrawideband radio technology [15], Bluetooth [16], and ZigBee [17] that have enabled the implementation of body sensor networks. Seminal work in this field by Jovanov et al. [17] has been followed by extensive work toward the development of strategies aimed at optimizing the scarce resources available on the nodes of body sensor networks [18]. This latter work has required the development of operating systems specifically designed for body sensor networks.

Advances in e-textile research have paralleled the vast achievements in body sensor networks. Seminal work in this area was performed at Georgia Tech, where researchers developed the Wearable Motherboard or Smart Shirt [19]–[21]. The concept pursued by researchers at Georgia Tech, led by Jayaraman, was one of transforming the clothing items into an equivalent of a computer bus by attaching sensors, for example, to an undergarment that could communicate with a data logger positioned on the subject (e.g., at waist level). This concept led to different implementations and, eventually, commercially available products. An example of a research platform of this type is shown in Figure 3(a), which is developed by Wade and Asada [22]. In this implementation, traditional sensor technology is embedded in special buttons that carry sensor technology and that clip onto the fabric in a way that allows an electrical connection with a data logger positioned at waist level via the garment. The layers of the garment provide electrical characteristics that allow one to use the garment itself as a modem line, thus providing a means to send data from the sensors to the data logger.

Others have attempted the actual development and integration of sensing elements into garments using new materials and techniques to integrate sensors and fabric. De Rossi's group has provided a unique contribution in this field [23], [24]. Figure 3(b) shows an example of a technology developed in his laboratory. Conductive elastomers are printed on a lycra shirt and provide a means to monitor movements of shoulder and elbow. The method leverages changes in resistance of the sensing elements that occur as they are stretched or released during the movement of body segments. Such changes are detected using a circuitry that injects a small constant current into the sensing elements and by means of a dedicated high-impedance amplification unit that reads changes in voltage drop on the sensing elements that are associated with changes in their resistance. Current research focuses on the implementation of a new generation of textile sensors [24]. These new technologies are expected to allow one to seamlessly record electrocardiogram data, monitor respiratory rate, track changes in blood oxygenation, and monitor sweat rate.

Wireless and e-textile technologies are now integrated into wearable systems that fulfill the promise of subjects' long-term monitoring in the home and community settings. Researchers are relying on data loggers with advanced communication capabilities (such as Internet tablets and smartphones) to gather data from wearable sensors and relay clinical information to a remote location [25]–[27]. Although technical problems still hamper the deployment of these systems (e.g., difficulties managing the resources of smartphones thus leading to rapidly depleting the phone battery), this is a fast evolving field that has shown incredible transformations over the past few years, and therefore, it is anticipated that these issues will be soon addressed. Among others, the development of open-source smartphone platforms promises to make available to researchers and developers an array of tools that will likely result into suitable solutions for an effective integration of smartphones into wearable systems.

The body of work summarized earlier is by no means a complete review of the advances that we have witnessed over the past decade in the field of wearable sensors and systems. However, it provides an overview of the efforts and results achieved by researchers in the field of wearable technology toward developing systems that are suitable for clinical applications. In the past, lack of suitable platforms for unobtrusive long-term monitoring of individuals in the home and community settings hindered the application of wearable technology to concrete clinical problems. Advances achieved in this field over the past decade have made available to researchers and clinicians the tools needed to pursue clinical studies. As a consequence, we are currently witnessing a flourishing of research efforts focused on assessing the use of wearable sensors and systems to

prevent diseases, promptly respond to emergency situations, and optimally manage chronic diseases. This is expected to be the focus of the field for the next five to ten years. Preliminary results summarized later suggest that major clinical applications of wearable technology are just around the corner.

Shifting the Focus on Clinical Applications

Clinical applications enabled by wearable systems can be categorized according to how their design addresses the three main challenges inherent in monitoring individuals in the home and community settings. These challenges are captured by the following three questions.

1) How critical is the information to be gathered and relayed by the wearable system?
2) How long will the subject wear the system and during performance of what type of motor activities?
3) How quickly will it be necessary to relay the information gathered by the wearable system to a remote site?

These questions work to define how applications of wearable technologies have been pursued in the recent past and are currently pursued with renewed effort, thanks to the advances in wearable sensors and systems described earlier. Knowing whether the information gathered via wearable systems is critical to the management of emergency situations or to the prevention and diagnosis of diseases has somewhat determined the level of comfort of researchers and developers in the private sector in pursuing related applications. When critical information needs to be recorded and potentially processed by the system, developers must use stringent criteria for the assessment of the reliability of the data. They also need to consider the liability of the company manufacturing the wearable system. It follows that research and development activities focused on these applications proceed slowly compared with research and development activities that address applications handling information that is not as critical. How long a subject needs to wear the system to gather relevant information also

(a)   (b)

Fig. 3. Examples of e-textile technologies developed over the past ten years. (a) A system developed by Wade and Asada (22) relying upon special buttons that carry sensor technology to record physiological and movement data. (b) A system developed by De Rossi's research team (23) for monitoring the movements of the shoulder and elbow via recordings of the voltage drop on conductive elastomers that are printed on the garment. (Figures used with permission.)

appears to be a determinant factor in making a decision about pursuing the applications of wearable technology. The longer a subject has to be monitored, the more stringent will be the specifications concerning unobtrusiveness of the system and its wearability. Consequently, the first applications researchers have focused their attention on require only sporadic data sampling. In other terms, the system is donned and doffed as needed but not used for continuous monitoring 24 hours a day, 7 days a week.

Similarly, the type of activity individuals are engaged in significantly affects the system requirements. For instance, if subjects are monitored while exercising, the quality of physiological data gathered by the wearable system will be a concern, because movement artifacts so often negatively affect the quality of physiological signals. Finally, applications in which critical information must be gathered by the wearable system and used to generate alarm messages for immediate response to a life-threatening situation present challenges that only complex systems that have undergone extensive testing can meet. The full development of such systems is yet to come, as only recently reliable technologies that meet the specifications of this type of monitoring have been made available.

These considerations justify the initial focus of researchers and developers in the field of wearable sensors and systems on wellness [28]–[30] and activity monitoring [31]–[36]. Figure 4 schematically represents a common application of wearable technology in this context. In the figure, a runner's heart rate, respiratory rate, and motion are monitored using wearable sensors. A cell phone provides data-logging capability and connectivity. Commercially available systems already provide the capability shown in Figure 4, including the ability to locate the subject via solutions based on a global positioning system. This ability enables a runner to follow his/her position on a running course via a display unit mounted on the wrist and to compare performance from one day to another while running or after completing the running course. Wearable solutions are also used by runners to pace themselves by playing suitable music using an MP3 device wirelessly connected to sensors embedded in the subject's shoes that also track his/her pace.

Wellness applications of the type described earlier should not be dismissed as mere gizmos. They have, in fact, a great potential to increase exercise compliance in populations at risk. Obesity management is an example where application of wearable systems that support wellness could be implemented [37]–[40]. It is well known that we face an obesity epidemic and that the weight management industry is a huge business that delivers very limited results. More effective tools are required in the fight against obesity, and wearable sensors and

systems have the potential to provide new tools to support and encourage healthy choices. For example, smartphones and software applications can be designed to display activity profiles comparing target levels and actual levels of activity as assessed via processing data gathered using wearable sensors. Subjects could then be encouraged to increase their activity level via presentation of this type of information on the smartphone display. Furthermore, the use of a global positioning system and contextual information (e.g., the time of the day and the proximity to a cafeteria) would trigger positive messages about decreasing calorie intake by suggesting healthy nutritional choices. The potential impact of tools of this type on preventing diseases and chronic conditions such as diabetes and cardiovascular diseases is significant, and current research continues to make positive strides in this direction.

Paralleling the progress in wearable technology, applications gradually shifted their focus toward medical problems that require enhanced reliability compared with systems designed for wellness applications. Monitoring patients with Parkinson's disease to improve clinical management of symptoms is an example of one such type of application. Currently, clinical visits are inadequate to sample the severity of parkinsonian symptoms, because symptoms vary in response to a medication dosage with a time constant of hours, a time interval that does not lend itself to direct patient observation by
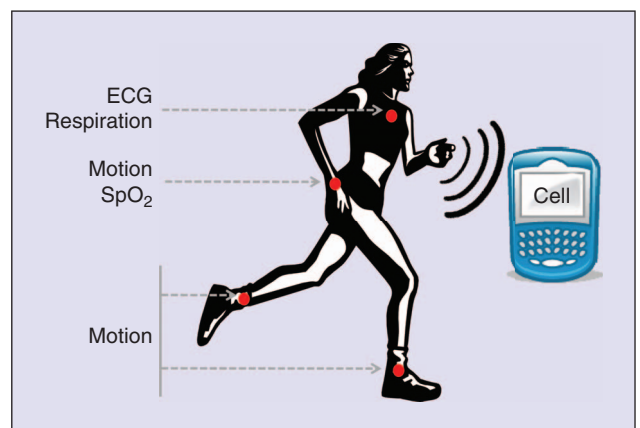

Fig. 4. An important application of wearable technology consists of monitoring individuals while they exercise. The focus here is on wellness/fitness monitoring, with the potential development of methodologies to improve exercise compliance. Wearable sensors allow one to monitor movement, respiratory rate, and heart rate. ECG: electrocardiographic recordings; SpO_2: oxygen saturation.

clinical personnel. Furthermore, patients do not have an objective perception of their own motor status, and thus they cannot report reliably about the severity of their symptoms and their response to a medication adjustment. Patients often mix up symptoms (e.g., tremor and dyskinesia) that require opposite adjustments in medication intake.

Wearable technology has the potential for addressing these problems by providing a means of gathering objective measures of the severity of symptoms over a period of time sufficient, for instance, to reliably assess the effectiveness of medication adjustments. Seminal work by Ghika et al. [3] and Spieker et al. [4] exploring the use of sensor technology to capture the severity of parkinsonian symptoms was followed by the work by Keijsers et al. [41]–[43] aimed at assessing the effectiveness of medications in attenuating the severity of symptoms using wearable sensors. More recent research has been focused on integrating and further developing these techniques into complete wearable systems for home monitoring of patients with Parkinson's disease [44]–[46]. We anticipate that home monitoring of patients with Parkinson's disease will be integrated in the near future with remote assessment tools leveraging videoconferencing and remote access to sensor data to facilitate clinical evaluation of the severity of parkinsonian symptoms. Figure 5 shows a software application recently developed by Matt Welsh's research team and my research team (supported by the Michael J. Fox Foundation) as part of a joint effort toward the development of Web-based applications devoted to the collection of data from patients with Parkinson's

Fig. 5. Home-monitoring applications would often benefit from technology for remote examination of patients. The screen capture presented shows the graphical interface of an application recently developed by Matt Welsh's research team at Harvard University to monitor patients with Parkinson's disease in the home. The software application provides clinicians with access to wearable sensor data and measures the severity of parkinsonian symptoms (45).

> **O**besity management is an example where application of wearable systems that support wellness could be implemented.

disease in a home environment. The system integrates wearable technology and advanced signal processing algorithms to relevant information gathered to determine whether a medication adjustment is needed. The project has the overall objective of facilitating clinical management of parkinsonian symptoms in patients at the late stages of the disease.

The screenshot shown in Figure 5 is the software interface for personnel overseeing the remote clinical evaluation of a patient with Parkinson's disease. The session in Figure 5 is a simulation in which a subject posing as a clinician instructs a subject posing as a patient to perform motor tasks associated with the motor section of the Unified Parkinson's Disease Rating Scale, a clinical scale designed to assess the severity of parkinsonian symptoms [47]. Data gathered using a body sensor network are collected by a laptop computer (the patient's workstation) and relayed to the clinical site via the Internet. As the display of data on the clinician's computer screen occurs online, the clinician has the opportunity to spot-check the quality of data gathered during the session.

Similar applications have been pursued to monitor cardiovascular diseases such as congestive heart failure, which requires long-term monitoring of patients to detect worsening of patient status, and to set in place prompt interventions that might prevent hospitalization [48]–[50]. It is worth emphasizing that these applications can be seen as fulfilling the vision that led to the proposal of Holter monitoring in the late 1940s and its clinical adoption in the 1960s. Although Holter monitors have provided an invaluable tool to diagnose cardiovascular diseases over the past 50 years it could be argued that only by leveraging wearable technology can the vision that originated Holter monitoring be fully implemented.

While applications described earlier have significant potential clinical impact, they still fall within a group of applications that do not require prompt interventions in response to an emergency situation that would be detected based on the analysis of data gathered using the wearable system. In other words, these applications are designed around a clinical response with a relatively long time constant, namely, a few days. However, a new set of clinical applications of wearable systems is currently emerging that requires either a response within a few hours or an immediate clinical response, as sensor data gathered in such applications are meant to detect emergency situations. Applications that fall in this category include monitoring patients with chronic obstructive pulmonary disease to achieve early detection of exacerbation episodes, monitoring patients with epilepsy to detect the occurrence of seizures, and monitoring individuals to detect and potentially prevent sudden cardiac arrest. These are all applications of great relevance because of the potential-related improvement of patients' quality of life and because of the significant potential impact on the society at large.

In patients with chronic obstructive pulmonary disease, early detection of exacerbation episodes would break the downward spiral that characterizes these patients who worsen every time they experience an exacerbation episode—a worsening from which they never fully recover—leading to a progressive decline of their clinical status. In patients with epilepsy, the detection of seizure events could potentially prevent severe accidents and even death if the patient falls unconscious and clinical care is not provided promptly. In individuals at risk of sudden cardiac arrest, continuous monitoring of heart rate could provide a means to guarantee that clinical care is immediately provided if the heart suddenly stops beating.

The applications of wearable sensors and systems summarized in this section demonstrate the potential of this technology for achieving prevention and diagnosis of several diseases and for optimally managing chronic conditions. Some of these applications, specifically those related to wellness management, have already led to commercially available systems. More challenging clinical applications such as the use of wearable sensors and systems to facilitate the titration of medications in chronic conditions (e.g., Parkinson's disease) are bound to become clinical tools within a few years. The need for high reliability of the system, as required by clinical applications with a focus on providing an alarm that guarantees prompt interventions in response to emergency situations, still requires both technology development and clinical testing. New trends merging wearable technology and robotics appear to have the potential for opening the way toward improved home interventions and achieving higher reliability in the detection of emergency situations.

New Trends: Integrating Wearable Technology and Robots

The combination of wearable technology and robots is a very recent development in the field of wearable sensors and systems [51], [52]. Interest in this approach originates from the observation that subjects with chronic conditions (such as hemiparesis following a stroke) could benefit from therapeutic interventions that can be facilitated by robotic systems and enhanced by wearable technology. Figure 6 provides an example of how robotic and wearable technologies can be combined to deliver therapeutic interventions. In the simulated clinical session shown in Figure 6, a subject is posing as a patient with hemiparesis undergoing therapy. An exoskeleton-type system provides support to the hemiparetic arm, thus facilitating the performance of movements. The position of the exoskeleton is tracked using sensors embedded in the device. The output of the tracking algorithm is used to play video games designed to encourage the patient to perform motor tasks such as reaching and grasping/retrieving objects. Performance of these motor tasks is known to have positive therapeutic effects when

subjects perform a high number of movement repetitions. A sensorized glove is used to track hand grasp/release movements, thus providing a platform for the implementation of exercises focused on the recovery of hand function.

The aforementioned approach is expected to benefit subjects undergoing physical therapy to recover arm and hand functions. The combination of wearable technology (i.e., the sensorized glove) and robotics allows one to improve the quality of the intervention. The robot alone does not lend itself to the implementation of therapeutic exercises that focus on hand function, an aspect of physical therapy that is known to be of paramount importance when one aims at achieving recovery of the subject's functional capability. The sensorized glove is therefore a key factor in improving the clinical intervention in the presented application scenario. Patients that are candidates for the use of these technologies include individuals who have suffered a stroke, a traumatic brain injury, or experienced other neurological problems leading to impairments and functional limitations of the upper limbs.

It is important to note that traditional physical therapy techniques could theoretically lead to similar results to the ones expected from robotic therapy (although recent research suggests that robotic therapy leveraging interactive games leads to better results than therapeutic interventions simply based on delivering a high number of repetitions of specific movements [53]). However, the intensity of the exercise that has been shown to benefit patients when robotics is relied upon cannot be achieved in the current health-care system model by means of traditional interventions based on manual therapy administered by clinical personnel in a one-to-one ratio with patients (i.e., with one therapist working with a single patient at a time). This is because the number of physical therapy sessions that are reimbursed by insurance companies is limited. Also, it must be observed that a higher number of movement repetitions can be achieved within a single session using robotics compared with traditional therapeutic interventions. In this context, wearable technology provides a means to enhance available rehabilitation robotic platforms

Fig. 6. Rehabilitation robotics is combined with wearable technology for the purpose of enhancing functions that are not provided by robotic systems (51). Features provided by commercially available robotic systems like the one shown in this figure (Armeo by Hocoma AG) can be augmented via the use of wearable sensors. In the example presented, a sensorized glove provides the system with the ability to implement exercises targeting the recovery of hand function. This capability would not be available if the robot were to be used alone.

The use of off-the-shelf interactive gaming systems is very attractive in the context of implementing home interventions, but commercially available systems lack the ability of monitoring movement patterns in a way that is satisfactory from a rehabilitation intervention standpoint.

that lack adequate focus on exercises devoted to the recovery of hand function.

The future of these technologies is in the home. Home-care services would oversee the use of systems like the one described earlier implemented in a home setting. During their visits, therapists would instruct patients on the correct ways to perform therapeutic exercises using the robot and combined wearable technology. Patients would exercise using interactive games that rely on the hardware provided by the home-care service. Data concerning exercise compliance and performance would be logged by the system for later review by the therapist and patient. The data would also be relayed to a clinical center for monitoring purposes so that immediate action can be taken if necessary (e.g., a telerehabilitation session could be set up if inappropriate patterns of movement are observed via review of data collected during performance of a home-exercise session).

In addition to improving the effectiveness of interventions by combining rehabilitation robots and wearable technology, one can think of a number of other applications that would be facilitated by the deployment of robotic and wearable technologies in the home. Major changes could rapidly occur in the field if home robots were combined with wearable technology, as schematically represented in Figure 7. In this example, a wearable sensor suit is used to monitor movement and physiological data [Figure 7(a)], and the suit communicates wirelessly with a home robot [Figure 7(b)]. The figure shows a picture of the iRobot ConnectR (courtesy of iRobot). This system has features including a Web camera and Internet capability. In this way, leveraging wearable technology and home robots could have a dramatic impact in the field of clinical home monitoring.

Additionally, Figure 8 shows a range of clinical applications that could be pursued if one leveraged home robots and wearable technology. The platform depicted in Figure 8 is complex and relies upon a combination of wearable sensors, home robots, interactive gaming, and other technologies (e.g., cell phone and Internet tablet) to develop a connected health application for patients with balance disorders. The system assesses fall risk via monitoring stride variability, facilitates interventions delivered using interactive gaming systems, and detects falls via the combined use of wearable sensors and a home robot.

Methods for the assessment of fall risk based on the variability of gait that have been proposed in recent years [54], [55] could be implemented using the platform shown in Figure 8. Wearable sensors attached to the ankles would allow one to detect foot strike events and estimate stride-to-stride variations in the duration of the gait cycle. The platform shown in

Figure 8 would also provide connectivity with interactive gaming systems like the Nintendo Wii. Physical and occupational therapists have demonstrated a growing interest in the use of off-the-shelf interactive gaming systems as a tool that complements traditional clinical interventions. The use of off-the-shelf interactive gaming systems is very attractive in the context of implementing home interventions, but commercially available systems lack the ability of monitoring movement patterns in a way that is satisfactory from a rehabilitation intervention standpoint. While using interactive gaming systems, subjects must be encouraged to use appropriate motor control strategies (rather than compensatory mechanisms). In the scenario shown in Figure 8, the system would provide appropriate feedback during the performance of home exercises, based on the analysis of data recorded using wearable sensors. The sensors would be used to monitor movement patterns, and a home robot would be relied upon to convey feedback to the individual. Finally, wearable sensors and home
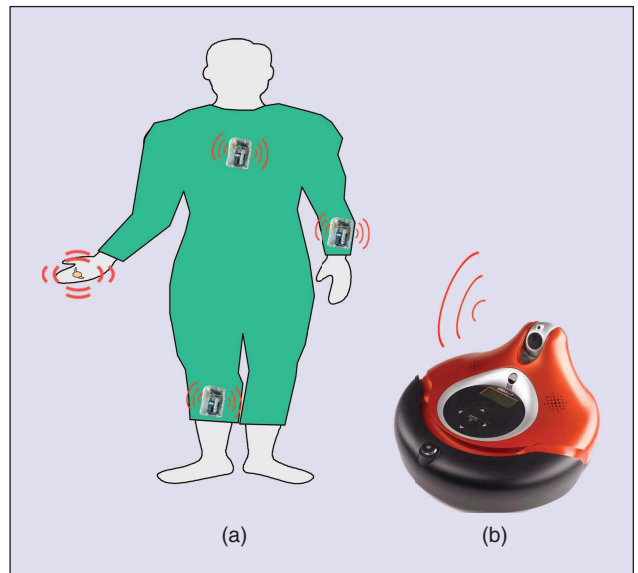

Fig. 7. It is envisioned that combining (a) wearable technology and (b) home robots will result in novel home-monitoring applications. Wearable sensors will communicate wirelessly with home robots (image courtesy of iRobot) that will in turn respond to alarm messages using onboard capabilities (i.e., image processing) to interact with the patient and assess the severity of the situation.

robotics would be combined to achieve prompt detection of falls in the home environment. A key factor in minimizing the severity of fall-related injuries is to promptly detect the fall event and alert clinical personnel. During the past decade, a number of devices for fall detection have been developed by researchers [56]–[60], and fall-detection devices have been introduced on the market. These systems are typically based on body-worn units (e.g., pendants and wrist straps) equipped with an accelerometer. The units are programmed to detect falls based on the analysis of accelerometer data and to send an alarm message to a caregiver. Unfortunately, the potential benefit of these systems is limited by poor compliance, because subjects are overwhelmed by the large number of false detections of falls (i.e., false positives) that mark existing systems. This is somehow inevitable because fall-detection systems have to be extremely sensitive to the occurrence of a fall. To achieve high sensitivity, low specificity (i.e., high rate of false detections) has to be tolerated. In the system shown in Figure 8, a home robot is combined with the use of a body-worn unit to minimize the number of false positives. The body-worn unit sends a message to the robot when the unit detects a fall. The robot responds by using a combination of video processing and human–robot interaction techniques to assess whether the subject actually fell. If the robot determines that the subject fell or if it cannot determine whether the

individual fell, it alerts a caregiver. The caregiver has the ability of teleoperating the robot to determine if the individual fell, and if so, how urgently is attention to the situation required. This approach based on assessing potential fall events with a home robot has the potential to significantly improve the effectiveness of fall-detection systems. By autonomously eliminating a large number of false positives and allowing for a rapid assessment of the severity of true positives, the system allows precious human care-giving resources to be deployed in the most efficient and effective manner.

It is worth noting that the combination of home robots and wearable technology is somewhat complementary to installing sensing components in living environments [61]. Although some applications might be better served by sensing components installed in the home [62], [63], the use of home robots has a significant potential for decreasing costs and mitigating the level of obtrusiveness of the monitoring system. It is known that robots are often perceived by people as pets. Therefore, one would expect that a home robot would be more easily accepted than a set of Web cameras positioned in all the rooms of the home. Home robots are also easier to control, and they provide the assurance that privacy is not violated. For instance, the camera positioned on the robot can be easily flipped so that the lens does not face the subject, thus reassuring individuals that the privacy is not violated even by
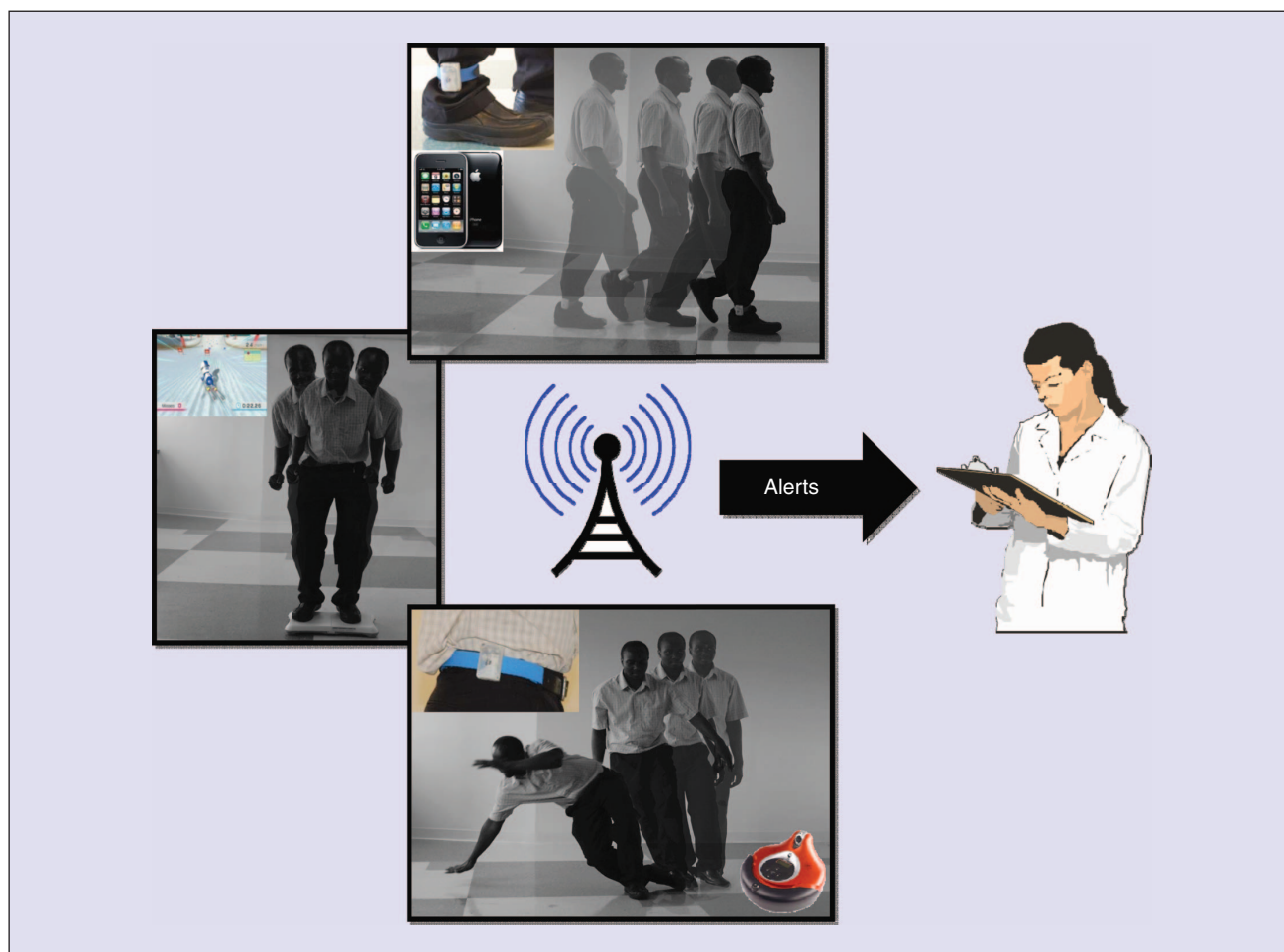

Fig. 8. Complex systems under development will soon provide enhanced monitoring capability, the ability to facilitate clinical interventions, and features that are suitable for detecting emergency situations, assess needs (e.g., via gathering images and other information using a home robot), and alert a remote clinical center when necessary.

mistake. Besides, remote control of home robots provides a flexibility of interaction with the monitored individual which is virtually impossible to achieve using sensing components (including Web cameras) installed in the home environment. It follows that home robots, alone or in combination with a limited set of sensors embedded in the home environment, have the potential to achieve effective monitoring of individuals in a rather unobtrusive way and with very limited likelihood of generating privacy concerns.

In summary, platforms combining home robots and wearable systems could be used in a variety of home-monitoring applications ranging from the detection of seizures in patients with epilepsy [64] to the detection of cardiac arrest in patients undergoing cardiac monitoring [65]. Emergency situations would be detected via online processing of data gathered by wearable sensors, and an alarm message would be sent to the home robot. The robot would wake up (if it is in standby mode at the time it receives the alarm message) and check upon the patient's condition. The system would provide high detection sensitivity without the drawback of requiring human intervention every time a false-positive detection occurs. Connected health software applications would further enhance the platform by assuring that qualified clinical personnel are promptly put in touch with the patient when he/she needs it the most, i.e., during an emergency situation. Therefore, this type of platform could have a significant impact on our ability to clinically manage long-term conditions associated with impairments and functional limitations that compromise the individuals' quality of life.

Conclusions

It is now more than 50 years since the time when clinical monitoring of individuals in the home and community settings was first envisioned. Until recently, technologies to enable such vision were lacking. However, wearable sensors and systems developed over the past decade have provided the tools to finally implement and deploy technology with the capabilities required by researchers in the field of patients' home monitoring. As discussed, potential applications of these technologies include the early diagnosis of diseases such as congestive heart failure, the prevention of chronic conditions such as diabetes, improved clinical management of neurodegenerative conditions such as Parkinson's disease, and the ability to promptly respond to emergency situations such as seizures in patients with epilepsy and cardiac arrest in subjects undergoing cardiovascular monitoring.

Current research efforts are now focused on the development of more complex systems for home monitoring of individuals with a variety of preclinical and clinical conditions. Recent research on the clinical assessment of wearable technology promises to deliver methodologies that are expected to lead to clinical adoption within the next five to ten years. In particular, combining home robots and wearable technology is likely to be a key step toward achieving the goal of effectively monitoring patients in the home. These efforts to merge home robots and wearable technology are expected to enable a new generation of complex systems with the ability to monitor subjects' status, facilitate the administration of interventions, and provide an invaluable tool to respond to emergency situations.

Acknowledgments

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