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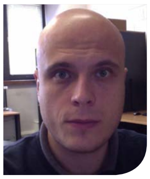
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Multimedia and Gaming Technologies for Telerehabilitation of Motor Disabilities

Rehabilitation for chronic conditions resulting from acute or progressive disease might be delivered in an outpatient facility as in the case of telerehabilitation, self-rehabilitation and, more generally, in the context of home-based rehabilitation to improve the patients' quality of life. Here we present the emerging field of home-based applications for continuous digital health, focusing in particular on low-cost rehabilitation systems for motor disabilities based on multimedia and gaming technologies. Innovative technologies for telerehabilitation are illustrated. We also present recent advances in telerehabilitation, considering the most relevant projects that best represent new trends for research and development of new technologies and applications in this context.

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Telerehabilitation (TRH) is the provision of rehabilitation services at a distance using information and communication technologies (ICT) [1]. TRH services might be needed for diagnosis, assessment, consultations, and monitoring, as well as to supervise therapies or therapeutic settings or to propose interactive therapies. Rather than being described as a super specialization of rehabilitation, therefore, TRH should be viewed as an alternative way to deliver rehabilitation services, particularly suited for chronic conditions that might benefit from home-based care. It has been demonstrated, in fact, that improving motor function, a major goal of any rehabilitative treatment, should be pursued even in the chronic stages of disabling condition, like stroke, Parkinson's disease, and multiple sclerosis, for which telemedicine could be seen as a great opportunity to allow remote diagnosis and clinical monitoring.

The aim of this article is to present the emerging field of home-based applications for continuous digital health, focusing in particular on low-cost TRH systems for motor disabilities that adopt diffused ICT for gaming and multimedia as well as the networking connection of these technologies through the Internet for remote monitoring and control. We will discuss the basic characteristics of such systems applied to TRH, also considering the current projects under assessment. The main issue for all the laboratory settings pertains to the cost of the equipment and the complexity of the required infrastructure. This prevents domestic use and hence, the patient would not be able to follow his rehabilitation program outside the medical facility. However, technological developments in ICT for multimedia and gaming may allow the design of increasingly accessible TRH systems, enabling continuous remote monitoring of patients in their home environment.

In the current literature, there are several examples of the efficacy of TRH strategies. In stroke patients, 6 weeks of upper limb training conducted by means of laptop mediated TRH improved clinical and kinematic outcome measures [2]. A TRH intervention composed of televisits, daily use of an in-home messaging device, and telephone intervention calls, resulted in a significant improvement of physical function, persisting up to 3 months in 52 veterans with stroke [3]. A virtual-reality based treatment delivered via the Internet was found more effective than a traditional physical therapy program in a group of 36 stroke survivors, leading to better motor performances [4]. Despite promising results, however, a recent Cochrane meta-analysis including 10 trials involving a total of 933 stroke patients participating in TRH program found insufficient evidence to reach conclusions about the effectiveness of TRH after stroke [5].

One issue to be addressed when examining the potential role for TRH is its suitability for conducting proper functional and/or biomechanical diagnoses in order to have standardized examination of patients' impairment severity prior to any treatment, and to track training results. In rehabilitation these aspects appear challenging because they are often related to an objective analysis of residual abilities and movements. Instrumental movement analysis might be particularly useful for these purposes, but it is usually performed in a laboratory setting where different components can be used to simultaneously record biomechanical data, both for lower and upper limb movements [6]. Particularly, a movement analysis foresees the evaluation of: 1) kinematic variables involved in the description of movement (i.e., linear and angular displacements, velocities, and accelerations) by means of goniometers, accelerometers or imaging measurement techniques, such as those involving optoelectronics; 2) kinetic variables, i.e., the forces causing movement and the resulting energetics, by means of force transducers; and 3) activation of muscles, by means of surface electromyography.

This article also seeks to explore, what is the real burden of TRH. If, from one side, it could allow reduced hospitalizations and personnel costs, on the other side it is evident that the technological needs for TRH might be expensive. Moreover, while user and health professional satisfaction with TRH is generally good, the availability of TRH resources remains scarce. Home automation systems have been available for several years, but their spread, both in domestic contexts and more generally, in building automation has increased recently. Among the factors that have led to this new trend are a greater availability of devices, more controlled costs, and a growing interest around issues such as energy saving, safety, and quality of life, with particular emphasis on people with a physical disability. Moreover, increased prevalence of full Internet connectivity makes remote monitoring of home-based systems by experts working at hospital or other medical centers more affordable. In light of these considerations, it might be expected that costs will continue to fall, at least related to technologies. Studies specifically aimed at calculating costs of TRH are therefore needed.

Innovative Technologies for Telerehabilitation

Recent research has shown that impairments and disabilities can be reduced by intensive and repetitive rehabilitation, but inpatient, supervised rehabilitation is often associated with high costs. For this reason, supervised inpatient rehabilitation is reserved for acute phases of disease. A growing body of evidence supports the use of TRH for individual with physical disabilities [7].

First, a reliable patient monitoring technique for TRH should automatically record and classify patient's motion during training sessions, and then suitable data fusion and pattern recognition procedures must be used for movement analysis and classification, as adopted so far in multimedia applications [8]. High motion variability due to patients' body function impairment can significantly increase the classification difficulty. The main goal of this task is to elaborate on kinematic information about limbs acquired from standard video and sensor arrays. In this way, kinematic analysis can be done outside of a biomechanics laboratory. The analysis can be obtained by defining a model to be applied principally to healthy subjects that will be capable of efficiently differentiating complex rehabilitation exercise movements. The motion capture system must be accurate enough to capture movements performed by patients suffering from various degrees of motion impairment, and it should be suited for rehabilitation training environments with no or reduced medical supervision, such as a patient's home or a community center. Indeed, several studies have demonstrated that machine learning systems are useful in biomedical signal processing as, for example, for grouping among gait variables or for multifunctional prosthesis control [9].

Among the most common approaches are different technologies that have been developed in recent years to capture a person's movement. To reveal and classify among the different kinds of motions, different technologies are commonly adopted to capture upper extremity kinematics. Current technologies allow us to carry out this task using several methodologies. It is possible to distinguish between two broad categories of motion capture methods: optical systems (equipped or not with markers) and non-optical systems (electromechanical, inertial, magnetic, and acoustic). A comparison of technological and clinical pros and cons regarding the most innovative systems adopted for TRH is summarized in Table I:

- Optical systems rely on infrared cameras that capture the scene where the subject is moving. In marker-based optical systems, the subject is provided with suitable markers capable of reflecting infrared radiation appearing as bright spots in the scene. The resulting image is a two-dimensional projection of a three-dimensional scene, which can be reconstructed by means of triangulation from at least two cameras, requiring a suitable calibration task. The accuracy of the result depends on the kind of markers used. Non-optical systems use several types of sensors for measuring biometric and motion data.
- Electromyography (EMG) systems are able to extract the peripheral source that generates tremor, i.e., the muscles, by recording the electrical manifestation of muscular contraction, thanks to the use of needles or surface electrodes.
- Inertial measurement unit (IMU) based motion tracking systems are commonly considered as most suitable for TRH applications, due to their advantages of being compact, cost-effective, and relatively easy to operate compared to their counterparts such as visual-based tracking systems [10]. They are able to capture the movement of a person by placing acceleration and angular rate sensors on the body surface.
- RGB cameras, depth sensors, and their combination called "RGB-D sensors" present the advantage of a higher spatial resolution, although they can be affected by the noise introduced by obstruction and/or problems relevant to the angle of view. They have made possible the development of an uncountable number of applications in the field of human-computer interaction (HCI). Such applications, varying from gaming to medical, are useful because of the capability of such sensors of elaborating depth maps of the placed ambient. Many researchers have focused on designing RGB-D cameras for biomedical applications.

In recent years, many devices have been used as an alternative tool to capture human movement. In particular, there are some low-cost approaches to TRH by means of the Microsoft Kinect sensor, which not only has changed the meaning of controller in computer gaming, but it is also transforming the way we interact with every technological device [11]. The possibility of rehabilitating two young adults with motor impairments using a Kinect-based system in a public school setting has been investigated in [12]. An interactive game-based rehabilitation tool for balance training of adults with neurological injury has been developed and assessed in [13], while the authors of [14] applied Kinect to the problem of passive fall risk assessment in home environments. The use of Kinect and other natural gaming systems for developing effective tools to aid rehabilitation in clinical settings has been also focused in [15]. The concurrent validity of Kinect against a benchmark reference, a multiple-camera 3D motion analysis system in 20 healthy subjects during three postural control tests, has also been assessed in [16].

A typical integrated system composed by innovative technologies able to capture the movement in a remote context is illustrated in Figure 1. The patient needs to have installed at home a monitoring and detection system based on one or more RGB-D devices and wearable IMU sensors. Thanks to these devices, the data processing system is able to track the patient's movements, their clinical status and the degree of rehabilitation, without the direct *in situ* supervision of a doctor or physiotherapist. A network gateway is used to transmit the sampled information and the doctor will be able to see the data remotely, using a user-friendly interface that eases reading and should allow for a quick and easy interpretation

Table 1. Pros and Cons of the Technological and Clinical Aspects Associated with Innovative Systems for TRH.

TRH System	TECHNOLOGICAL Pros	TECHNOLOGICAL Cons	CLINICAL Pros	CLINICAL Cons
Marker-Based Optical Systems	High sample rates, suitable for fast movement, like in sports. Can accommodate large capture areas.	The subject must be provided with one or more markers and the accuracy depends on the kind of marker used.	Highly standardized systems for clinical movement analysis.	Require a dedicated laboratory, not always available in clinical settings. Time consuming.
EMG	Very accurate, and with the capability of following small movements of the arms.	Needs initial setup and medical support during the registration of the data to be analyzed.	Allows definition of muscle activation during movement. Useful for determining co-activations and muscle synergies.	Does not give information about the quality of muscular activation. Potentially affected by cross-talk phenomena.
IMU	Real time, easy setup, compact, cost-effective.	Sensitivity to interference for magnetic systems, limited range, not always suitable for very fast moves.	Portability. Useful for movement analysis in real settings (home, gym, outdoor).	Requires technical skills for post-processing analysis.
RGB-D	The cheapest and the better result considering a higher spatial resolution that these systems are able to achieve.	Needs cleaning and post-processing, occlusion areas can occur. Only for human tracking.	Easy to use. Availability. Reproduces clinical movement analysis and diagnosis allowing off-line evaluation.	Generally allows only subjective evaluation.

of data for generating feedback to the patient.

TRH systems may benefit from the use of the Internet as they provide the ability to use a set of very useful services and approaches. For instance, the opportunity to exploit remote systems for distributed computing can make the use of one of the aforementioned technological approaches computationally more affordable than using local hosts. In addition, the Internet allows us to exploit the cloud repository for both data and algorithms, in order to lighten the workload for the local device. This distributed approach enables the activation of mobile entities for diagnosis and analysis of patients, avoiding the need for laboratories with expensive equipment and onerous methodologies. Internet approaches can allow the implementation of other support services for patients and the clinical personnel, such as web or mobile applications for interactive training, skills updating, and so on. The Internet computing paradigm sets up a basis for the implementation of pervasive and ubiquitous systems, which are able to produce transparent, miniaturized, self-replacing systems in the context of the forthcoming Internet of Things.

New Trends and Research

Several recent research projects have proposed ICT solutions and TRH applications through multimedia and gamification techniques for the rehabilitation of patients with physical disabilities. An overview of the most recent and effective best practices follows, so as to give an outlook on new trends regarding TRH:

- *Rewire* - Rehabilitative Wayout in Responsive Home Environments project (http://www.rewire-project.eu) is a rehabilitation platform based on an innovative application of virtual reality, with the purpose of creating a customized health system that can be individually performed by patients in their homes, to improve their recovery after disease, and to avoid excessively long hospital stays. The platform consists of three hierarchical components: the patient station, which allows the patient to follow a path through rehabilitation involving mini games; the hospital station, used by staff in hospitals to define rehabilitation treatment, selecting exercises and showing improvement; and the networking station, which allows data collection about

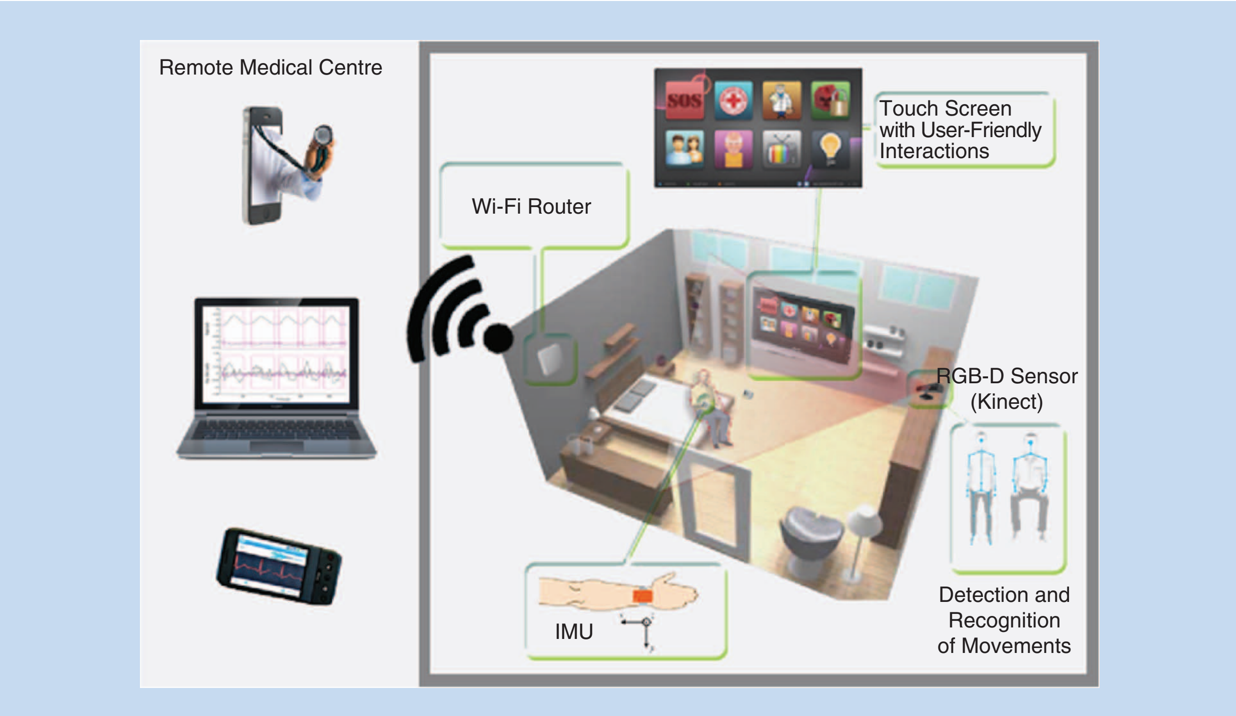

FIGURE 1. Operating scenario of a home-based TRH system.

rehabilitation tasks, enabling the multiparametric analysis of the patient behavior.

- *Stroke Recovery with Kinect* project (http://research.microsoft.com/en-us/projects/stroke-recovery-with-kinect), carried out by Microsoft Research Asia and the Seoul National University provides a virtual reality system to help patients in improving their movements based on Microsoft Kinect. This approach relies on a specific rehabilitation program designed like a game: in its tasks, the patient has to perform special exercises, getting a score based on quality, speed, and accuracy of execution. The analysis of the acquired data is performed by machine learning algorithms, which consider also the correlations between data from multiple patients.
- *Jintronix* project (http://www.jintronix.com) is designed to provide a tool for doctors to speed up the rehabilitation process, making it more engaging and helping the patient to a quicker recover and to their fullest potential. The system is still based on the use of Kinect and has a very low cost. The project provides an immediate feedback to patients about the correctness of the execution, while doctors can remotely monitor the data in order to customize the exercises.
- *XSENS* (https://www.xsens.com/customer-cases/interactive-sonification-human-movements-stroke-rehabilitation) aims at studying the arm movement of a subject by the positioning of two sensors, one on the upper arm and one on the forearm of the patient. The platform provides to the patient with acoustic feedback to check the correctness of the execution of the exercise. In order to obtain a system with the features previously described, the project adopts a low power and low latency hardware platform for the analysis of the sensors' data and for the sound composition.
- *AMMR* - Mixed Reality Rehabilitation (http://ame2.asu.edu/projects/mrrehab) is a rehabilitation system designed to analyze the movements of stroke survivors using a Kinematic Impairment Measure (KIM), which is an index made *ad hoc* for this purpose. Patients are required to execute different top games and the KIM index is evaluated to assess the quality of the execution of patient's movements.
- *Mercury* - A Wearable Sensor Network Platform for High-Fidelity Motion Analysis (http://fiji.eecs.harvard.edu/Mercury) is a platform composed of several wearable sensors that are applied directly on the subject body, and a base station that is installed at the patient's home,

as illustrated in Figure 2. This tool could be applied to several diseases that affect a person's movement. It has been tested on a subject affected by Parkinson's disease, and is in development for epilepsy.

- *CareToy* - A Modular Smart System for Infant' Rehabilitation at Home based on Mechatronic Toys (http://cordis.europa.eu/project/rcn/108029_en.html) is a project to provide a useful tool for infants with neurological diseases. In order to reduce costs and augment the clinical effectiveness of the therapy, several multi-sensor toys are used to help infants in rehabilitation at home. As depicted in Figure 3, the system is composed of three different modules: a sensorized mat, used to evaluate postural control; a vision module, for evaluating the infant's movement; and an instrumented baby gym with mechatronic hanging toys, used by the infant to test their movements.
- *Rehab@Home* (http://www.rehabathome-project.eu/project) is an infrastructure based on commercial low-cost devices, such as Kinect or Nintendo Wii, which create virtual environments for the users, using of "exergames" that make the rehabilitation path more engaging and attractive. With the aim of reducing the clinical cost of the rehabilitation path, this solution could be applied directly at the patient's home where the doctor could monitor the rehabilitation path, changing the difficulty and the type of exercise.
- *OPTI-RERC* - Optimizing Participation through Technology for Successful Aging with Disability (http://www.isi.edu/research/rerc/center_projects/project2.php) is a project providing virtual reality and gamification in home-based motor assessment. To acquire movement information, it makes use of commercially available cheap technologies such as Nintendo Wii, Sony Eyetoy, etc. The patients that can benefit from this platform are those affected by ictus. In particular, this platform analyzes the movement of upper limbs, lower limbs, and balance impairments.
- *Tele-rehabilitation solution for stroke patients to boost physical recovery* (http://news.nus.edu.sg/highlights/7560-tele-rehabilitation-solution-for-stroke-patients-to-boost-physical-recovery) is a project that tests the effectiveness of telerehabilitation systems. To provide a powerful instrument for the patient, this platform is equipped with applications on tablet for both patients and doctors, sensors to capture movement, and "live" video conferencing to allow communication between the two parties.
- *Play4Health* (http://www.play-4health.com) is a rehabilitation platform based on therapy and videogames for making a patient's rehabilitation activity more engaging. It is intended to be used at different assistance levels, such as in hospital, health centers, or most important, in the patient's home. In addition, in this case movements are captured by low-cost devices easily available on the market. Several games are adopted to evaluate the correctness of the movements of the patients.
- *SENIOR* - Sensing Systems for Interactive Home-Based Healthcare and Rehabilitation (http://inertia-technology.com/senior-sensing-systems-for-interactive-home-based-health-care-and-rehabilitation) is a home-based healthcare system designed using wireless sensors that support patients in their everyday lives. This project combines both technologies from high-tech companies and research institutes or healthcare centers from The Netherlands.
- *Home based Automated Therapy of Arm Function after Stroke via Telerehabilitation*

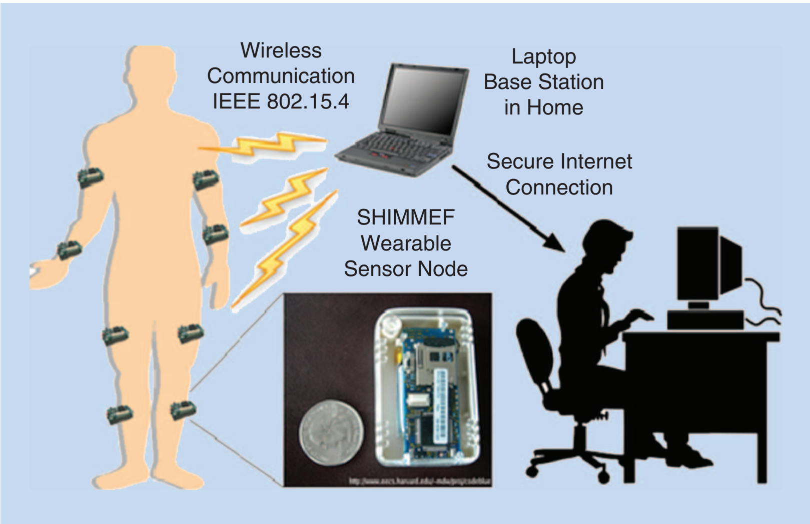

FIGURE 2. Functional structure of the Mercury project.

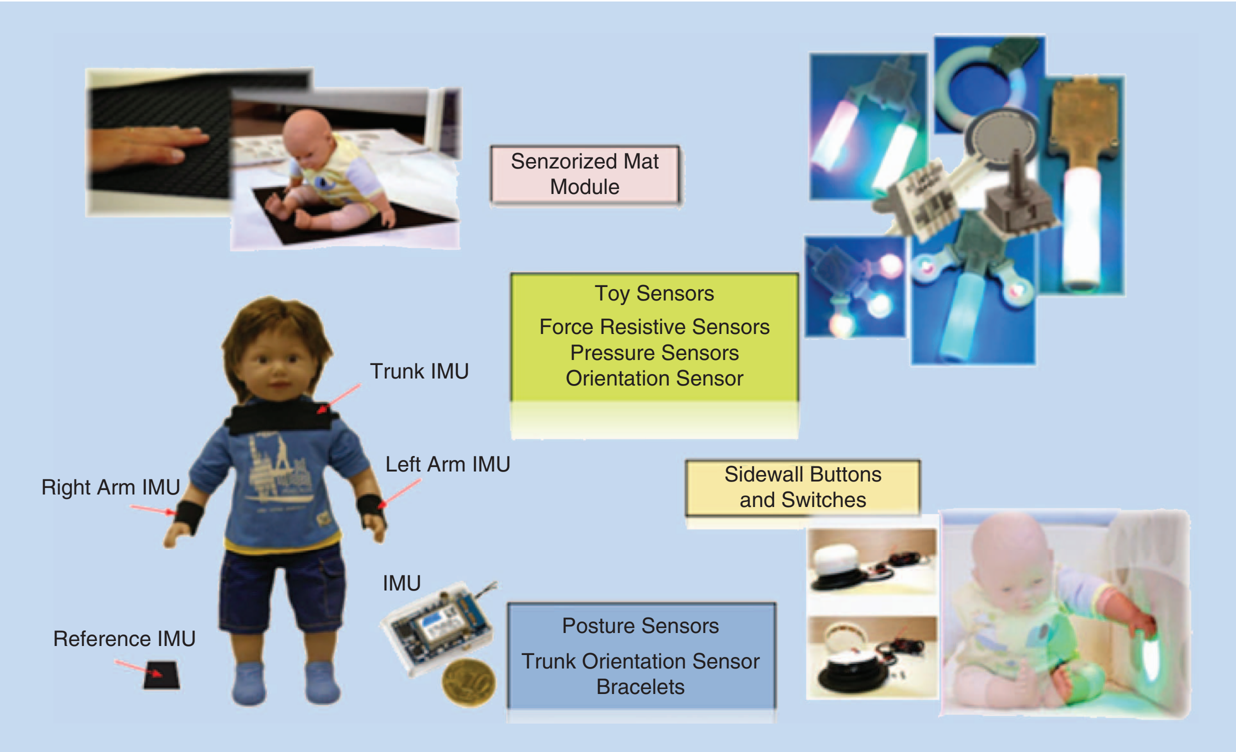

FIGURE 3. Modules and technologies adopted in the CareToy project.

(http://cabrr.cua.edu/research/Telerehabilitation.cfm#telemed) develops a device (i.e., *AutoCite*) to analyze the upper extremity tasks, while also providing adequate graphical feedback to the patient. This system could be use at the patient's home and could be a potential and inexpensive tool for evaluating the therapies for upper extremities. It is also a powerful telemedicine platform used by clinicians and researchers at the National Rehabilitation Hospital (NRH) of Dublin, Ireland.

Home Based Rehabilitation

In this paper, we have discussed basic characteristics of ICT systems belonging to the emerging field of home-based applications for TRH of motor disabilities. We have also presented innovative technologies based on multimedia and gamification techniques that able to reconstruct a patient's movements and perform rehabilitation analysis with the use of low-cost sensors, such as Kinect, which only needs a computer for data processing. These experiences represent a first step towards systematic introduction and utilization of such systems, which are already diffused for multimedia and gaming in many homes. These measures will enable territorial continuity of health assistance within the growing paradigms of e-Health, Well-Aging, Smart Cities, and the Internet of Things.

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VIEWPOINT *(continued from page 19)*

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