Immersive Physiotherapy: Challenges for Smart Living Environments and Inclusive Communities

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Abstract. The ability to deliver therapeutic healthcare remotely relying on pervasive computing technologies requires addressing real research challenges ranging from sensing people and their interactions with the environment to software abstractions to move data from low-level signals into representations that are understandable and manipulatable by domain experts who are not computer scientists. In this position paper, we inspect the potential for *immersive physiotherapy*, just one of many potential application of real smart health. The time is right for delivering real services for immersive physiotherapy, as many technological solutions for remote monitoring of patients and their interactions are ready for prime time. In this paper, we take a critical look at remaining tasks, to propose novel concepts for data processing and service delivery of remote physiotherapy applications. We go beyond the obvious integration tasks to uncover real and tangible research challenges that are solvable in the near term and, when solved, will make the vision of immersive physiotherapy possible.

Keywords: Smart health · Middleware · Immersive physiotherapy

1 Introduction

Recent visions of pervasive computing have considered the potential for using emerging technologies in support of *smart health* in a variety of ways. Black et al. [1] envisioned that as pervasive computing develops, there will be an evolution from isolated "smart spaces" to more integrated enterprise environments where the dream of unconstrained, ubiquitous, pervasive computing will face the realities of enterprise requirements, market forces, standardization, government regulation, security, and privacy. The authors defined pervasive healthcare, based on pervasive computing, as the conceptual system of providing healthcare to anyone, at anytime, and anywhere by removing the restraints of time and location while increasing both the coverage and quality of healthcare. Physiotherapy, or physical therapy, refers to the act of treating disease, pain, or malformations

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of the body through exercise and stimulation rather than through surgery or medication.

Physiotherapy treatment includes physical examination of joints' ranges of motion, muscle length, and muscle power. Given assessments of needs, physiotherapists advise caregivers and family members on appropriate exercise regimens, however there is no way to ensure that these regimens are correctly followed or even carried out on a regular basis. Current practice requires frequent manual examinations, coupled with expensive equipment for assessment and therapy. This approach requires the physical proximity and dedicated attention of a highly trained physiotherapist, potentially making insufficient use of his skills and expertise. Furthermore it necessitates transportation of the patient (who is often elderly) from his home or nursing home to the hospital for each visit or for the therapist to perform services in the home.

Given the increasing availability of pervasive computing technologies, patients implicitly find themselves immersed in environments capable of supporting complicated physiotherapy routines in a transparent and natural way that encourages the patient's interaction with both the physical and digital environments. Briefly, our vision of pervasive computing assisted physiotherapy is one in which a patient can follow a prescribed exercise and physiotherapy regimen at anytime and in any place while being monitored and guided by digitally augmented physical objects embedded in their natural spaces. Therapists can be provided detailed dynamic and adaptive regimens and can monitor their patients' progresses and capabilities at a very fine grain. In this paper, we describe this vision, novel concepts on architectural and middleware design and identify key research challenges that exist in making it a reality. At a high level, our identified research challenges fall in the following categories:

- **Augmenting the environment.** Realizing the vision of immersive physiotherapy includes ensuring that the physical and digital environments are connected through sensing and actuation. Objects must be embedded with the ability to capture physiotherapeutic measures, and the algorithms and protocols that calibrate, sense, aggregate, and communication environmental data must support relevant physiotherapy data.
- **Defining regimens.** Therapists must be able to define physiotherapy polices, which requires a detailed representation of the physical objects in the immersive environment, their therapeutic capabilities, and their ability to measure their own interactive physical aspects. This representation must be abstracted to a level of understanding that matches the therapist's ability to define a therapy regimen, and the policies must feed back into the immersive environment's smart objects and the patient's interactions with them.
- **Middleware for delegation and integration.** The heterogeneity of patients' immersive environments, the distribution of therapists, patients, and their smart objects, and the vast quantities of information generated require a set of abstractions embodied in a middleware that coordinates the right amount of information to the right components or users at the right time.
- **User interfaces.** Building on the wealth of research that exists in interactive interfaces with digitally augmented objects, immersive physiotherapy requires

interactive constructs tailored to the therapy domain, which include the ability to give instructions on physical movements and to provide a wealth of feedback, including tactile feedback, using metrics of those physical movements.

The advancement of sensing, computing and communication technology and the omnipresence of smart devices in our everyday space can bring this vision of immersive physiotherapy to millions of users in their home environments. In particular, an immersive physiotherapy system can act as a virtual doctor who follows and monitors patients through their routine everyday tasks in their natural spaces. In this position paper, we explore how pervasive computing research can help to make this vision a reality and expand on these fundamental research challenges. A framework that supports this vision of immersive physiotherapy has other obvious potential use cases and benefits, for example as a fitness monitor [2] and assistant [5] or as an assistant in working with special needs children [4].

2 Research Challenges

The challenges in realizing the vision of immersive physiotherapy as we have described it are many. Several of the challenges, especially those related to resource discovery and network infrastructure (e.g., related to *cloudlets*) have been addressed or are the focus of significant other efforts. In this section, we highlight challenges that are inherent to the pervasive physiotherapy and their integration with other existing advancements. Specifically, we focus on challenges in four categories: (*i*) augmenting the environment; (*ii*) defining regimens; (*iii*) middleware for delegation and integration; and (*iv*) user interfaces. This vision also demands real interdisciplinary collaboration between engineers and clinicians to understand the various requirements and their impacts from a medical perspective.

2.1 Augmenting the Environment

Immersive physiotherapy is a true pervasive computing application in which the physical and digital worlds are inherently intertwined. People, the environment, and objects in that environment are all actors in the application and must all be augmented with devices that can sense and actuate.

One of the crucial related challenges relates to sensor placement and calibration. This has to include managing sensor signal variations due to the ambient conditions, including the nature of surrounding materials (e.g., clothing, skin, walls). However, extracting meaningful semantics from sensor data requires a mapping from signals to semantics, which may itself be dependent on a wide variety of context components. Manual calibration of these myriad sensors in the wide potential environments is, in the best case tedious and likely impossible. Therefore immersive physiotherapy demands *in situ* and on-going autonomous sensor calibration wherein individual sensor-specific calibration functions and parameters are learned while the application is live. Redundancy in sensing and actuation devices can aid in this process.

Further, these sensor networks integrated with the body, the environment, and objects in the environment present challenges in how to stream data from multiple sensor devices and synchronize those multiple sensor data streams simultaneously. For capturing fine grained human body movement, it may be necessary to transmit raw sensor data at high update rates [8]. This may deplete the battery power of the devices quickly and increases the challenges of supporting multiple sensing devices simultaneously. Alternatively, we must explore processing the sensor data locally on each device or on small clusters of devices and transmitting estimated features at a lower frequency. To perform in-network data processing and feature extraction, it is necessary to design a low complexity filtering algorithms suitable for these low powered devices and potentially tailored to the physiotherapy/fitness domain.

Traditional human motion capture technologies implicitly assume that movement of different segments of the body are independent and estimate their movement separately; therefore, the estimated motions often contain serious distortion [9]. To solve such distortion problems, algorithms must explicitly consider the skeleto-muscular structure of the human body. The degrees of freedom for any segment and the parameters to represent movement should be selected according to this structure. As a single example, the human body movement can be captured using angular velocities from gyroscopes and accelerations from accelerometers sensor. The collected acceleration and angular rate information can be fused by a Kalman filter [10] to reconstruct orientations of body segments in real time.

2.2 Defining Regimens

Therapists are not computer scientists. A high-level understanding of sensing and actuation must be enough for them to define complex regimens that can incorporate high degrees of expressiveness from the available sensors and actuators without requiring low-level sensor/actuator programming skills or even understandings. This has ramifications in two directions: (*i*) the level of abstraction with which users think about information in the immersive physiotherapy environment and (*ii*) the language and interfaces therapists, doctors, and caregivers use to get information out of the system and to define complex regimens.

In the first case, users of the immersive physiotherapy system think about high level pieces of information that are, at times, greatly distant from the low-level data that sensors acquire about the environment. What is required in these instances are mappings from these high-level specifications to the low-level sensors and actuators in the environment [6]. Such mappings should be automatic and transparent to the users.

In the latter case, what is necessary for the end user is an intuitive way to interact with a policy specification engine. Our previous work has looked at intuitive interfaces that build on web-programming techniques to provide natural ways for users to connect sensors and actuators in their environments [3]. For the immersive physiotherapy environment, what is needed is an additional layer of abstraction that frames these connections in terms of exercises and activities a patient can do given the available capabilities of the objects and the environment and the target state of therapy, whose progress is measured by the sensors.

2.3 Middleware for Delegation and Integration

The immersive physiotherapy environment will consist of a variety of wireless sensor devices which constitute the BSN, ESN and OSN. These devices will be highly heterogeneous, and the variability in a given deployment will be unpredictable. Given the availability of sensors to collect information about the environment and actuators to provide interaction, particular attention must be focused on selecting the *right* set of devices, given the defined regimen(s), the user and network requirements (e.g., on energy and communication costs), and the available capabilities. We have applied model-based regression techniques to select the most appropriate set of sensors to meet specified fidelity requirements for a high-level sensing task [6]; such approaches must be extended to also consider actuation and the joint optimization of competing regimens.

Different algorithms need to be evaluated and integrated into a middleware system that spans the immersive physiotherapy architecture, ranging from sensor information processing, data fusion, classification and clustering, human skeleton structure modeling, forward kinematic analysis, motion recognition, exercises assessment, etc.

Perhaps most importantly, delegation mechanisms must be designed that monitor the context and choose the best set of infrastructure components to meet the required tasks given the available resources. For example, if the patient is away from his home, the middleware must decide how to allocate processing capabilities to available cloudlets given the user's requirements for processing, dynamics, and data privacy. These aspects must be traded off against the need to seamlessly monitor the patient's interactions with his environments. Similar problems have been tackled in choosing the right sets of network interfaces for a task [7]; we will focus on extending these ideas to consider the context of processing in addition to network interfaces.

2.4 User Interfaces

An immersive physiotherapy or fitness system must be intuitive to use. It is inevitable that, to capture users' spontaneous interactions with different devices and sensors present in the surrounding environment, it is necessary to employ advanced gesture and natural interaction recognition. We do not want users to have to learn to interact with the environment and the therapy objects; we want the environment and the objects to learn how the user interacts with them. For example, time series algorithms such as dynamic time warping may be useful in measuring and learning the similarities between two time series of sensor readings for comparing them and drawing conclusions.

In addition, the points at which the patient and caregiver interact with the system must be user friendly and attractive. The system should be designed to inherently motivate normal users to follow their regimens without being insulting or annoying and without requiring constant guidance from the therapist.

The displays may need to incorporate three-dimensional graphics for rendering aspects of the therapy regimen. In addition, relying on elements of the environment, including objects in the environment to serve as part of the user interface is important for ensuring continuous and correct interactions between the patient and his therapeutic environment.

3 Conclusion

Our vision of immersive monitoring of individuals' health and wellness, specifically, in this paper, as it pertains to physiotherapy is an essential component of the vision of future home-based healthcare. While we have maintained a focus on the use of remote monitoring for supporting physiotherapy, many other application domains share a very similar structure and purpose. Clearly, monitoring the fitness of generally healthy individuals and the manner in which their daily activities support a specified fitness plan is quite similar, although potentially without some of the detailed monitoring and timing constraints necessary for physiotherapy. The same notions of instrumenting the environment, measuring the user's interactions with that environment, and using elements of the environment to motivate behavior are the same. Recent work has also looked at how to use pervasive computing to assess, motivate, and reach special needs children [4]; this infrastructure, when targeted to the characteristics and activities particular to a specific need can be used to support *in situ* monitoring of these children, which will lead to more natural interactions and information.

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