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Universidad del País Vasco
Euskal Herriko Unibertsitatea

COMPUTER SCIENCE FACULTY, DEPARTMENT OF COMPUTER LANGUAGES AND SYSTEMS

KIRES: A DATA-CENTRIC TELEREHABILITATION SYSTEM BASED ON KINECT

A thesis submitted in fulfillment of the requirements for the PhD degree in Computer Science by:

David Antón Sáez

Supervised by:

Dr. Alfredo Goñi Sarriguren

&

Prof. Arantza Illarramendi Echabe

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To my family and friends.

ABSTRACT

It is widely accepted that the worldwide demand for rehabilitation services and professionals will be growing, and this should influence the growth of telerehabilitation as there will be rising numbers of people across the world expecting, and needing, such services. To meet these needs, there will have to be developed systems of telerehabilitation that will bring services to even the most remote locations, through Internet and related technologies.

This thesis is addressing the area of remote health care delivery, in particular telerehabilitation. We present KiReS; a Kinect based telerehabilitation system which covers the needs of physiotherapists in the process of creating, designing, managing, assigning and evaluating physiotherapy protocols and sessions and also covers the needs of the users providing them an intuitive and encouraging exercise interface and giving useful feedback to enhance the rehabilitation process. As required for this type of multi-disciplinary projects, physiotherapists were consulted and feedback from patients was also incorporated at different development stages.

In short KiReS (Kinect Rehabilitation System) is a system that combines the following components: Microsoft Kinect as a motion capture device, an interactive interface with visual feedback that provides guidance for patients based on real-time exercise analysis, a real-time communication feature that puts patients and physiotherapists in contact streaming Kinect data, and an ontology that is aimed to assist in selection of suitable exercises for patients.

KiReS aims to outcome limitations of other telerehabilitation systems and bring some novel features: 1) *A friendly and helpful interaction* with the system using Kinect and motivational interfaces based on avatars. 2) *Provision of smart data* that supports physiotherapists in the therapy design process by: assuring the maintenance of appropriate constraints and selecting for them a set of exercises that are recommended for the user. 3) *Monitoring of rehabilitation sessions* through an algorithm that evaluates online performed exercises and sets if they have been properly executed. 4) *Extensibility*, KiReS is designed to be loaded with a broad spectrum of exercises and protocols.

Several user studies were performed to evaluate the accuracy of the exercise recognition algorithm and validate the engagement with the system.

RESUMEN

Es ampliamente aceptado que la demanda mundial de servicios y profesionales de rehabilitación es cada vez mayor, y esto va a influir en el crecimiento de la telerehabilitación, ya que habrá un número creciente de personas en todo el mundo que esperan y necesitan tales servicios. Para satisfacer estas necesidades, habrá que desarrollar sistemas de telerehabilitación que puedan llevar estos servicios incluso a los lugares más remotos, a través de Internet y las tecnologías relacionadas.

Esta tesis se encuadra en el área de prestación de servicios sanitarios a distancia, en particular, telerehabilitación. En ella presentamos KiReS, un sistema de telerehabilitación basada Kinect que cubre las necesidades de los fisioterapeutas en el proceso de creación, diseño, gestión, asignación y evaluación de protocolos de fisioterapia y sesiones, así como las necesidades de los usuarios, proporcionándoles una interfaz intuitiva, fomentando la realización de ejercicios y proporcionando información útil para mejorar el proceso de rehabilitación. Como es común en proyectos multidisciplinares, consultamos a fisioterapeutas y tuvimos en cuenta las opiniones de los pacientes en las diferentes etapas de desarrollo.

KiReS (Kinect Rehabilitation System) es un sistema que combina los siguientes componentes: Kinect como dispositivo de captura de movimiento, una interfaz interactiva que guía a los pacientes en base al análisis de ejercicios en tiempo real, una comunicación en tiempo real que pone a pacientes y fisioterapeutas en contacto transmitiendo datos de Kinect y una ontología que tiene como objetivo ayudar en la selección de ejercicios adecuados para los pacientes.

KiReS pretende superar las limitaciones de otros sistemas de telerehabilitación y aportar nuevas características: 1) Una *interacción amigable* con el usuario usando Kinect y características motivacionales basadas en avatares. 2) *Suministro de datos utiles (smart data)* que apoyan a los fisioterapeutas en el proceso de diseño de la terapia: asegurando el mantenimiento de las restricciones adecuadas y seleccionando conjuntos de ejercicios recomendados para el usuario. 3) S*eguimiento de las sesiones de rehabilitación* a través de un algoritmo que evalúa los ejercicios realizados y establece si han sido ejecutadas correctamente. 4) *Extensibilidad*, KiReS está diseñado para trabajar con ejercicios y protocolos asociados a diferentes patologías.

Además, se realizaron varias pruebas piloto con usuarios para evaluar la precisión del algoritmo de reconocimiento de ejercicios del sistema y validar el sistema con pacientes reales.

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David Antón Sáez

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Somewhere, something incredible
is waiting to be known.

Carl Sagan

CHAPTER 1 INTRODUCTION

During the last century, technology has developed tremendously allowing mankind to progress in most of the knowledge areas. Medicine has always been one of the most visible of these areas as its progress has lead to the continuous increase in life expectancy in Western countries. However, people higher survival to diseases and traumas that leave physical sequels are challenging aspects in the context of an efficient health management. The evolving telecommunications industry combined with medical information technology has been proposed as a solution to reduce health care cost and provide remote medical services.

For remote medical services, the telemedicine area has received a preferential attention because, in general, it promotes providing patients remote care without reducing the quality of care. Telemedicine can be applied for different situations that are nowadays widespread in the Western countries. In order to give a brief overview, we can mention strokes, surgical intervention recovery, and disabilities.

In the United States, stroke is a leading cause of disability, cognitive impairment, and death. Nowadays it accounts 1.7% of national health expenditures and, because the population is aging and the risk of stroke more than doubles for each successive decade after the age of 55 years, these costs are anticipated to rise dramatically [76]. The use of telemedicine in the treatment of stroke has shown great promise for improving patient access to recommended stroke treatments [95].

In many countries Total Hip Replacement (THR) is a common surgery. For example, the Agency of Healthcare Research and Quality (USA) reports more than 285,000 THRs are performed each year in the United States. This number is forecast to double in the next twenty years [58]. Following surgery, rehabilitation is a critical component for resuming normal activities of daily living, so telerehabilitation therapies are being promoted [93].

Nearly one in eight people have a disability in the United States. Statisticians reported that, in 2008, over 36 million people, or 12.1% of the civilian non-institutionalized population, had a disability. Nearly 19 million people reporting disabilities are of working age (18–64 years old) and over 4 million working-age people report having difficulty hearing, 3.4 million report vision difficulties, and 7.7 million report cognitive difficulties [96]. Furthermore, chronic conditions are currently responsible for 60% of the global disease burden, which may become 80% by 2020 in developing countries [10]. Research shows that many of the physiological and social impairments of chronic diseases can be self-managed at home through telehealth technologies and could potentially decrease the staggering medical costs associated with repeated hospitalizations and long-term services in chronic diseases [13].

These are only a few examples of the trends we are facing, the consequences of the aging population, the chronification of illnesses and the higher survival to diseases that leave physical sequels are challenging aspects in the context of an efficient health management.

In this thesis we concentrate in a telerehabilitation system. It is widely accepted that the worldwide demand for rehabilitation services and professionals will be growing, and this should influence the growth of telerehabilitation as there will be rising numbers of people across the world expecting, and needing, such services. To meet these needs, there will have to be developed systems of telerehabilitation that will bring services to even the most remote locations, through Internet and related technologies.

By and large, a telerehabilitation system allows monitoring and physiotherapy support of different groups such as: the elderly, disabled and sick, facilitating them contact with carers and improving their quality of life. Several studies indicate the therapeutic usefulness of telerehabilitation systems and tests based on virtual interaction have shown that they can be as effective as traditional treatments [87,112]. In addition, as it is relatively frequent abandonment of classical rehabilitation sessions because of boredom or disinterest, an important factor to consider is the motivating character of such systems.

A basic telerehabilitation system has at least one camera that allows a therapist to see the user and monitor therapy directly (videoconferencing). More complex systems include sensors that can record the movements of the user and evaluation mechanisms of the exercises. There exist a great variety of methods of interaction in which the movement of a person can be monitored. These methods can be divided according to the type of sensor used in three main groups: robot-assisted tracking, non-visual monitoring and visual monitoring [120]. The aim of these methods is to obtain data in real time about the position changes of persons and their body parts.

In this work, we have decided to use Kinect, an innovative natural interaction device developed by Microsoft™. Kinect is classified as a visual tracking system without markers that allows users to control and interact with applications using an interface that recognizes gestures, voice commands and objects without physical contact. Compared to other systems in which the user has to carry sensors on the body, Kinect is more comfortable and recognition does not suffer from marker occlusion problems. This technology applied to the field of telerehabilitation can create systems which by recognizing movements and gestures would be able to automatically evaluate therapeutic exercises performed by the user.

The development of a telerehabilitation system requires interdisciplinary collaboration to achieve a good result. Thus, in addition to software engineers for modeling and implementing the system, the intervention of experts in the field of rehabilitation, doctors and physiotherapists is required. The patients must be considered the third participant involved, as they will use the system and should feel comfortable and motivated using it.

1.1 Aims and scope

In this thesis we present Kinect Rehabilitation System (KiReS), a telerehabilitation system, for both the physiotherapist and users, that places special emphasis on the provision of a friendly and helpful interface, relies on Kinect's technology to analyze patients' exercises through the monitoring of the position of the body in space and provides smart data to users and physiotherapist. By smart data we mean, data that are obtained through a "semantic" perception process [44] which converts raw data into higher level abstractions that can provide insights and assist humans in making decisions. KiReS aims to overcome limitations of other telerehabilitation systems and bring some novel features that we summarize in the following:

- **Friendly and helpful interaction with the system**. This means that KiReS combines the use of a non-wearable motion control device with motivational interfaces based on avatars and dynamic exercise guiding, since rehabilitation depends largely on the user's motivation and compliance to be successful. Furthermore, KiReS facilitates physiotherapists an interface that is based on the therapy protocols they typically use with the added value that it provides an easy way to define new exercises.
- **Provision of smart data.** KiReS uses different techniques to provide actionable information. On the one hand, it manages a novel domain specific ontology that we have built, that supports physiotherapists in the therapy design process by: assuring the maintenance of appropriate constraints and selecting for them a set of exercises that are recommended for the user. This type of information is not provided by current systems and it has been recognized as very interesting by the consulted physiotherapists. On the other hand, it is able to convert low-level recorded Kinect data into high-level knowledge.
- **Monitoring of rehabilitation sessions**. KiReS incorporates an algorithm that evaluates online performed exercises and sets if they have been properly executed by comparing the obtained results with the recorded reference data. Automatic exercise evaluation is a key feature of our proposal, taking into account that, in home oriented telerehabilitation sys-

tems, it is crucial that the user is autonomously evaluated without the direct intervention of the physiotherapist during rehabilitation sessions.

- **Extensibility.** KiReS is not designed for a specific pathology; it can be loaded with a broad spectrum of exercises and protocols, as opposed to the majority of proposals that consider only a fixed number of exercises related to specific physical pathologies.

1.2 Context of this research

The research presented in this dissertation has been carried out in the University of the Basque Country UPV/EHU within the BDI research group. This project of telerehabilitation system has lead to the development of KiReS but also to fruitful collaborations with local and international institutions. Since the beginning physiotherapists from the Faculty of Medicine at the University of the Basque Country UPV/EHU have contributed to this work providing insight in the rehabilitation area. Given the interdisciplinary character of telerehabilitation, their collaboration was necessary, as computer engineers' vision might be limited. Internationally speaking it deserves highlighting the collaboration with the Telerehabilitation Research Unit at the University of Queensland, Brisbane, Australia and the Tele-Immersion Lab at the University of California Berkeley, Berkeley, USA. The outcomes of these collaborations have resulted in several publications in conferences and journals.

1.3 Technological context

In this section, we describe the context and some related works that have elements in common with the content of this dissertation. The technological aspects presented are:

- Telerehabilitation, the domain of the application.
- Kinect, the motion tracking device that acts as the core of KiReS technology.
- Specific research works in the telerehabilitation context

1.3.1 Telerehabilitation

The use of Health Information Technology (HIT) has been promoted as having tremendous promise in improving the efficiency, cost-effectiveness, quality, and safety of medical care delivery [35,39]. So, various telemedicine programs and technologies have been proposed to improve health management, reduce hospital re-admissions and the overall cost of care, and to reduce burden of travel for patients. Some of those programs are oriented to the telerehabilitation.

The World Health Organization (WHO) describes rehabilitation of people as a process aimed to achieve and maintain optimal levels of physical, sensory, intellectual, psychological and social functions. Rehabilitation covers various fields of health, including neurological rehabilitation, musculoskeletal rehabilitation, cardiac rehabilitation and general rehabilitation of the elderly [45].

The word *Telerehabilitation* was first used in a report by the National Institute on Disability and Rehabilitation Research of the US Department of Education in 1997, when a series of proposals for the new Center for Rehabilitation Research were published [114]. In that report the term "telerehabilitation" was used to describe the use of information and communication technologies in rehabilitation therapy.

Telerehabilitation falls under the broader term telehealth and it is defined as “the application of evaluation, preventative, diagnostic, and therapeutic services via two-way or multipoint interactive telecommunication technology” [107]. Telerehabilitation is a service provided by rehabilitation professionals delivered through telehealth technologies to clients at distant locations [13]. It should not be considered a technology in itself, but the use of new technologies to improve and optimize both rehabilitation services and patient outcomes. It is not intended to replace traditional rehabilitation services, but to strengthen them.

A driving force in the development of remote rehabilitation has been the rapid development of information technology and lower prices of computer and sensor devices. The increased use of technology by all generations and its use in all aspects of our lives have also contributed to the use of information technology to provide health services [98]. However, traditional rehabilitation usually requires a complex analysis, and treatment often involves several professionals and telerehabilitation will be only possible if the technology is able to provide the same complex interactions between the professionals and the patients. Finally, changes in health policy have also encouraged the development of remote rehabilitation. In particular, cost containment in healthcare systems while trying to maintain access to quality services has become indispensable in many Western countries that face an aging population [70]. The increased demand for rehabilitation services is generating pressure on existing services by the growing needs of an aging population. In addition, there has been a general trend towards shorter stays in rehabilitation centers [45]. Without a corresponding increase in resources and rehabilitation providers this pressure on existing facilities can lead to lack of services in not much time.

1.3.1.1 Benefits of telerehabilitation

The benefits of using telerehabilitation systems have the potential to go much beyond simply increasing access to these services. Telerehabilitation use can also lead to a better quality of service standard rehabilitation. These improvements in the overall quality stemming from improved evidence base for rehabilitation services, the design of truly functional outcome measures, and optimization of rehabilitation services [92]. Many countries are struggling to provide rehabilitation services in rural areas. Telerehabilitation can allow access to expert opinion, provide continuing education opportunities, reduce the need to travel and avoid interruptions in therapy [45].

Telerehabilitation has the inherent capacity to allow treatment in functionally relevant areas, such as the patient's home or workplace. This functional context must also allow the design of more meaningful measures for the therapist to those currently used [90]. A successful rehabilitation depends largely on patient motivation and compliance with therapy. Compliance is influenced by the environment in which it is carried out rehabilitation and the extent to which interventions adhere to cultural beliefs and family of the patient and their wishes. Telerehabilitation can open interactive communication channels, enabling daily monitoring of progress and timely treatment plans settings, which may improve adherence and motivation. Other ways, in which telerehabilitation can improve the quality of rehabilitation, include more timely and frequent evaluation and greater continuity of care [45].

Traditional rehabilitation takes place in rehabilitation centers or hospitals which requires patients to travel to appointments. This travel is often associated with both time and financial costs [22]. An alternate rehabilitation method is using telerehabilitation technologies where rehabilitation services are delivered directly into patient’s homes [7]. Research shows that telerehabilitation is, at least, as effective as usual care, and therapists can intervene effectively especially for those patients who have difficulty with transportation to rehabilitation centers [81,101]. Another advantage of these programs is an easy access by the health-care professionals to the data collected from users via the Internet and mobile devices [6,118]. Nevertheless, it is contrasted that telerehabilitation systems can provide an interesting alternative to traditional rehabilitation by delivering the service directly into patient’s home and data collected via sensors during sessions can be further processed to provide more effective health interventions [4,21,89].

Despite the many benefits that telerehabilitation can provide, its adoption is not yet widespread. Some rehabilitation techniques are necessarily excluded from telerehabilitation systems due to its manual nature [45]. However, for those that would be appropriate in telerehabilitation there are still a number of obstacles.

Technological barriers to the use of telerehabilitation are due in part, to poor access to technology or the limitations of the telecommunications infrastructure, both in relation to patients and to suppliers [49]. Accessibility issues within the technology itself (for example, user interface) are also often cited as the reason for this dysfunction. When users move to a new technology or a system that can be complex, hardware problems or interruptions in telecommunications services can easily discourage them. It is important that the development of telerehabilitation systems include human factors analysis and opinions of patients who will use it.

1.3.2 Kinect

Kinect is a natural interaction device developed by Microsoft Kinect® (Microsoft Corp., Redmond). It enables users to control and interact with the Xbox 360 console via an interface that recognizes gestures, voice commands and system objects and images, without physical contact [55].

Its first version was launched on November 2010 as a novel control device for Microsoft's Xbox 360 and sold 10 million devices in 4 months [119]. However, this success not only came from its use as a control device in videogames, but also because, in a short time, the research community found applications for which Kinect had not been designed originally [19]. The detection technology in Kinect competed directly with 3D cameras that were far more expensive. Nowadays, Kinect is becoming increasingly popular for research purposes given its low price and the quality and accuracy of its data [54].

The technology used in Kinect sensor was developed by PrimeSense who was the first to publish an SDK that allowed developing for the device (this SDK is part of the OpenNI organization). Also the hacker community through a process of reverse engineering developed an open SDK known as OpenKinect that works on multiple platforms. Microsoft released the official SDK for Kinect in June 2011, enabling the development of non-commercial applications and so increasing more the interest in the device [2,110].

Given the success of Kinect and the alternative uses that developers and researchers found for it, Microsoft launched in February 2012 a version of Kinect exclusive for Windows and also a new version of the SDK with new options for desktop applications. This new Kinect included new features compared to the Xbox 360 such as a new "close" mode for the depth sensor.

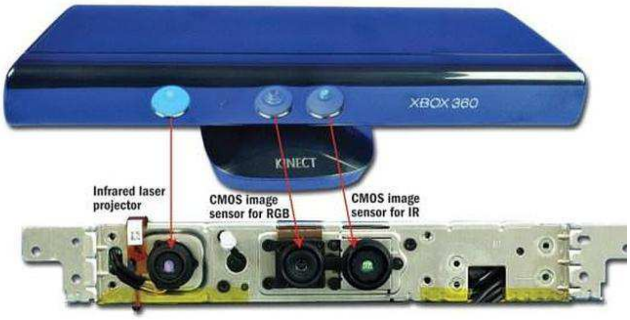


Fig. 1 - Kinect components

1.3.2.1 Technical features

Kinect consists of a video camera, an infrared-based depth camera and a series of four microphones. The data obtained allows visualizing the scene in 3D and providing information about the body and joints of the user. In addition, microphones allow voice recognition (see Fig. 1). This data is transmitted to the computer and can be processed to identify and classify the movements made by the user [55].

Sensors
Infrarred laser emiter
Infrared camera
RGB camera
Field of view
Horizontal vision: 57,5º
Vertical vision: 43,5º
Tilt range: ± 27º
Phisical limitation: 0,8 a 4 m
Practical limitation: 1,2 a 3,5 m
Data
320x240 16-bits 30 frames/sec
640x480 32-bits 30 frames/sec
16-bits audio at 16kHz
Tracking
Up to 6 people, 2 active players
Skeleton with 20 joints

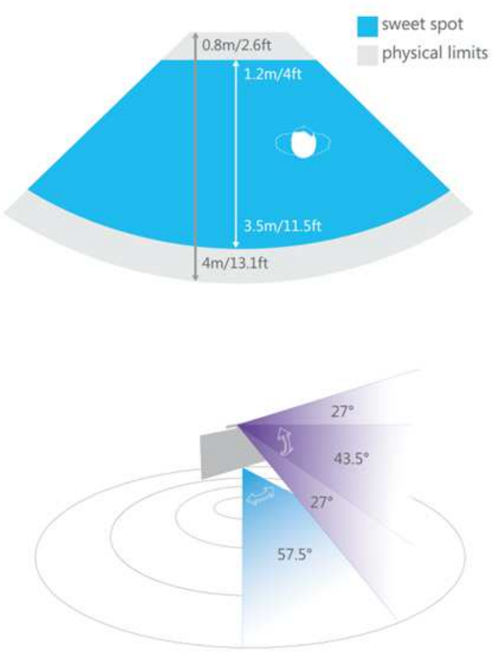


Fig. 2 - Kinect specifications

Depth measurement is done by a triangulation process. The infrared emitter projects a pattern of dots on the scene and the infrared camera captures this pattern and compares it to the initial reference pattern. Kinect processor analyzes the relative differences of each point and calculates the depth value for each pixel. The result is a depth image in which each pixel indicates how far this point is located. In Fig. 2 a summary [1] of the most relevant hardware specifications and software features of Kinect is presented.

1.3.2.2 Accuracy and performance

There are several works in which the accuracy of the data obtained from Kinect is evaluated [2,33,54,62]. In them various relevant aspects such as noise in the data, accuracy and data density are evaluated. Physical characteristics of the sensor that can affect performance are also discussed.

The resolution of the infrared camera determines the number of pixels used to represent a scene. Kinect allows multiple resolutions to the depth images (the highest is 640x480). Since the density of points is the number of points per area and the number of points remains constant, the dot density is inversely proportional to the square of the distance from the sensor [54]. Therefore it should be noted that the greater the distance between an object and the sensor less pixels representing that object.

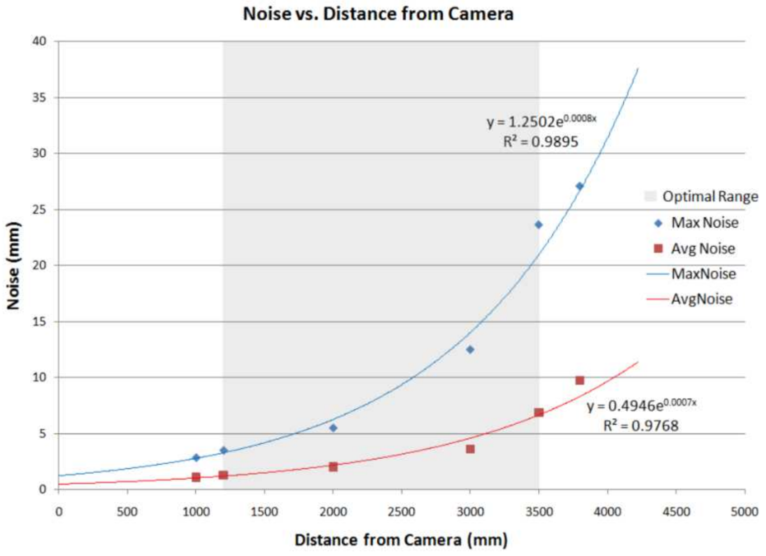


Fig. 3 - Relation between distance and data noise in Kinect

An important aspect is to establish the accuracy of the data obtained by Kinect and the noise that occurs in the readings. Both Andersen et al. [2] and Livingston et al. [62] conducted tests to measure the random noise in the data and in both cases the results were similar. In Fig. 3 it can be observed that noise increases exponentially with the distance from the sensor, although at the range of normal use (between 1.5 and 3.5 meters), the average error lies below 5mm. Moreover, readings also depend on the type of surface on which they are performed. The sensor is based on the projection of an infrared pattern, because of that, reflective and polished surfaces can cause "holes" in the depth image [54].

There have also been some analyses on physical characteristics of Kinect to determine if they affect the data. Experiments determined that there is angular distortion lens effect in the sensor readings. In addition it was found that there is a period of stabilization in the readings of Kinect. The data takes approximately 30 seconds to take its final and stable value. This effect also occurs if the device is moved or rotated abruptly. It is not something to consider except in cases where the device must be moved [2].

1.3.2.3 Kinect 2

Kinect 2 was launched on November 2013 as an improvement over the previous Kinect. Based on the same technology this new Kinect provides a higher video resolution 1920×1080, a new panoramic camera and new depth sensor capable 3D tracking at a higher resolution and precision. This new technology provided the framework for more accurate tracking capabilities, including a new skeleton with 25 joints (5 more than the first Kinect) and tracking for up to 6 active users simultaneously. Furthermore, the software gave access to deeper information on the skeleton, full joint rotation, facial expression tracking and facial recognition.

1.3.3 Research in telerehabilitation

Telerehabilitation research is constantly growing and, as in the field of traditional rehabilitation, there is a wide variety of assessment protocols and treatments to meet the heterogeneous nature of disability. Developing telerehabilitation protocols that are as effective and safe as traditional rehabilitation will be critical to the widespread application of telerehabilitation [45].

1.3.3.1 Telerehabilitation not using Kinect

Existing home telerehabilitation systems make use of different types of interaction devices and are oriented to the treatment of many physical pathologies. In a first approximation we can classify them into two main groups.

In the first group those works that propose to wear devices are included. Llorens et al. present Biotrack [63], a system for task-oriented games that evaluates whether people with cognitive impairment can reach some predefined locations. To that end, the system makes use of markers attached to the user’s body and infrared cameras. In [97] the authors use smartphone’s build-in inertial sensors to monitor exercise execution and to provide acoustic feedback on exercise performance and execution errors. Giorgino et al. [36] present a system that makes use of strain sensors attached to garments worn by users. The exercises evaluated are related with upper limbs (abduction/adduction of limbs, rotation of shoulders, etc.).

The second group includes those systems that advocate that users do not wear devices but they use low-cost non-intrusive tracking devices such as Nintendo Wii Remote or Kinect. In [69] the authors describe a telerehabilitation system, based on Nintendo Wii Remote, which uses an accelerometer to record the user´s movements in 3D. The system focuses on rehabilitation exercises of upper limbs. Lockery et al. [64] present a system that uses a webcam and adaptive gaming for tracking finger-hand movement. They attached trackers to some objects and a webcam captures user's hand and generates some metrics that provide information about the quality, efficiency, and skill of the user. More recently, in the context of hand evaluation, Iosa et al. [46] present a Leap Motion based rehabilitation system for elderly people that have suffered subacute stroke. This pilot study uses Leap Motion for conducting a videogame-based therapy that evaluates hand’s ability and grasp force.

An alternative approach to remote medical care delivery is the provision of specialized healthcare services to populations living in rural areas using remote monitoring technologies and video-conferencing. This approach has been expanding for several years and currently covers various specialty areas, such as prenatal care, cardiology, rehabilitation, stroke and others [8,12,13]. Until now the primary areas of video-based telemedicine have been in (a) simulation and training, (b) video-consultation and remote diagnosis, and (c) video-monitoring and vital signs tracking. However, recently several cost-effective commercial products have emerged that support secure real-time video connection between a health provider and a patient (e.g., Vidyo, VSee). Although such video monitoring has been quite successful for some specialty areas the remote physical therapy has been by and large lagging behind due to various reasons that among others include the cost of video equipment, insurance reimbursement model, and difficulty of obtaining reliable observations only from video while providing effective feedback to the patient remotely. Nevertheless, the distance barriers can be overcome by applying various forms of telecommunication, including voice, video, and virtual reality [10].

Concerning video transmission the majority of the tele-health systems have relied on single video transmission [68,79] which in case of physical therapy provides partial information on patient’s performance and hinders obtaining reliable observations (i.e., measurements) while providing effective feedback to the patient. Multi-view video or 3D video (RGB + depth) can on the other hand deliver additional information that can assist the physiotherapist in evaluating correctness of patient’s movements. When transmitting video, the network bandwidth is one of the major limitations in such applications. The use of standard RGB video compression techniques can significantly reduce the size of video transmission; however efficient compression and transmission of 3D depth data is still an open problem [57]. A real-time video/depth/audio transmission is essential to achieve a convenient and effective telerehabilitation session and positive user experience. Physiotherapist should be able to demonstrate exercises remotely to the patient while also being able to observe patient's performance. And the patients should be able to communicate to the physiotherapist any question or concerns about their performance. Avoiding cuts and delays in data streaming and guaranteeing the stability of the communication are still challenges in transmission of 3D video. With the objective of alleviating some of the issues in multimedia communication between various platforms and across different network configurations, an open source Real-Time Communications (RTC) framework, WebRTC, has been proposed [5,51]. WebRTC is a collection of standards, protocols, and APIs, which enables peer-to-peer audio, video, and data sharing in real time. Due to its implementation of secure communication protocols and platform independency, it is an ideal network framework for real-time interaction in remote physical therapy.

1.3.3.2 Telerehabilitation using Kinect

The Kinect camera has been to date applied in several aimed at physical rehabilitation [31,40,61,99]. Several studies have demonstrated that virtual interaction via telerehabilitation can provide additional benefits. For example, for the users, research has demonstrated that Virtual Reality (VR) game-based rehabilitation may be enjoyable and engaging [60] and provide a motivating setting for a wide variety of therapeutic goals [88,113]. This virtual interaction can be accomplished using motion capture technology [24,73,120] which has been shown to increase the intensity of rehabilitation and enhance user experience [43,87] when used in telerehabilitation systems. However, to be clinically useful, the motion capture devices must be simple to operate, reliable and have a high level of fault tolerance [9]. The recent advances in sensor technologies such as release of Microsoft Kinect camera [119] have facilitated cost-effective and relatively accurate acquisition of human movement [18,25,75] and its incorporation in the telerehabilitation field.

Among the telerehabilitation proposals that use Kinect two groups can be distinguished: proposals that make use of Kinect for Xbox; and those that make use of Kinect for Windows. Among the works of the first group we can mention [15,32,41,59,77,99]. In [59] the authors present a prototype of a game-based telerehabilitation system with Kinect that they have developed. However, their main goal is to prove the adequacy of using Kinect for telerehabilitation therapies and so they do not show technical details about the recognition method. In [15] Kinerehab is presented, an occupational therapy system based on Kinect, where users can perform three different exercises: lift arms front, lift arms sides and lift arms up. Chuan-Jun Su et al. [99] present a Kinect-based system to assist patients in conducting home-based rehabilitation. System's evaluation matched that of the therapist in 80% of the cases, and users' usability evaluation of the system was positive. Galna et al. [32] developed a Kinect-based rehabilitation game aimed at training dynamic postural control for people with Parkinson Disease. Participants stated that they enjoyed the game and also improved with practice. Finally, in Gotsis et al. [41] present 21 game concept prototypes which receive and process data sent by Kinect but the authors do not deal with the evaluation. Moreover, we want to mention the system presented in [77], which explores the combined use of inertial sensors and Kinect. They made an evaluation of different exercises (shoulder abduction/adduction, squat and sit to stand), but their goal was more aimed at performing online calibration of sensor errors than the evaluation of the exercises.

Concerning the works that use Kinect for Windows we can find, on the one hand, commercial products such as [28,37,50,106] which do not show many technical details concerning their internal behavior and are oriented to specific pathologies. On the other hand, there are research proposals that focus on different pathologies. Pastor et al. [80] and Chang et al. [14] have studied the feasibility of Kinect oriented to upper limb rehabilitation. In both works patients results were superior compared to those obtained during the first phases and systems acceptability by the patients was high. Gabel et al. [31] developed a method focused on full body gait analysis using Kinect. Results showed accurate and robust gait analysis using Kinect and its viability for diagnosis, monitoring and adjustments of treatments in domestic environments. Finally, Venugopalan, et al. [105] focus on the evaluation of fine motor movements (like hand and wrist movement) in patients with traumatic brain injury.

In this thesis, as some previous works, we try to exploit the potential of Kinect, a non-wearable device, in the area of telerehabilitation because we believe that the proposed solution would be less invasive for the user. It is worthy to point that, as one main limitation of existing systems is the limited number of exercises that they consider, this thesis also focuses on creating a extensible system that can cover different pathologies and provide novel features to assist physiotherapist in managing physiotherapy sessions.

1.4 Outline

This thesis consists of four chapters. In the first one, an overall view of the thesis is given: the motivation and goals and the context of this research. Also the technological context related to this work is explained.

The second chapter deals with the features of KiReS. A description of KiReS is given putting emphasis in the interface and the functionality.

The third chapter is centered on the different components of KiReS and the system validation.

The fourth chapter contains our conclusions, a summary of the contributions of this thesis and some future research lines. Finally, the last chapter contains the obtained publications.

Big Brother is watching you.

George Orwell, 1984

CHAPTER 2

KIRES: AN OVERVIEW OF KINECT REHABILITATION SYSTEM

Kinect Rehabilitation System (KiReS) constitutes the result of this research work. It combines all the aspects presented in this thesis and it is the purpose of the achievements and contributions made along these years. Even though KiReS is a merge of other technologies and processes this chapter is centered on the interface of KiReS and its functionality whose details are presented in the subsequent chapters. In short KiReS is a Kinect based telerehabilitation system which covers the needs of physiotherapists in the process of creating, designing, managing, assigning and evaluating physiotherapy protocols and sessions and also covers the needs of the users providing them an intuitive and encouraging exercise interface and giving useful feedback to enhance the rehabilitation process. All this is achieved using a wide range of technologies from image processing to data mining including knowledge representation or semantic technologies.

2.1 Architecture

KiReS is a telerehabilitation system that places special emphasis on the provision of a friendly and helpful interface for both physiotherapists and users. KiReS makes use of Kinect's technology to analyze patient’s exercises through the monitoring of the position of the body in space. This means that, KiReS deals with a non-invasive motion control device, and so users are relieve of carrying wearable devices. Moreover, KiReS includes motivational features in the interface such as avatars as successful rehabilitation depends largely on the user's motivation and compliance with therapy. For physiotherapists KiReS facilitates an interface that is based on the therapy protocols they typically use. It allows the physiotherapists to define sets of exercises (that constitute the therapies) for the users by a) using exercises already stored in a library, b) combining those stored exercises, or/and c) defining new customized exercises simply by recording them in front of Kinect. With this last possibility, the physiotherapists can define a great variety of exercises useful for many different therapies (or treatments) and define protocol that once integrated in the ontology can be used for reasoning and knowledge extraction on exercises and users. The architecture of KiReS is divided into modules that handle the functionalities provided for the users and the physiotherapists (see Fig. 4).

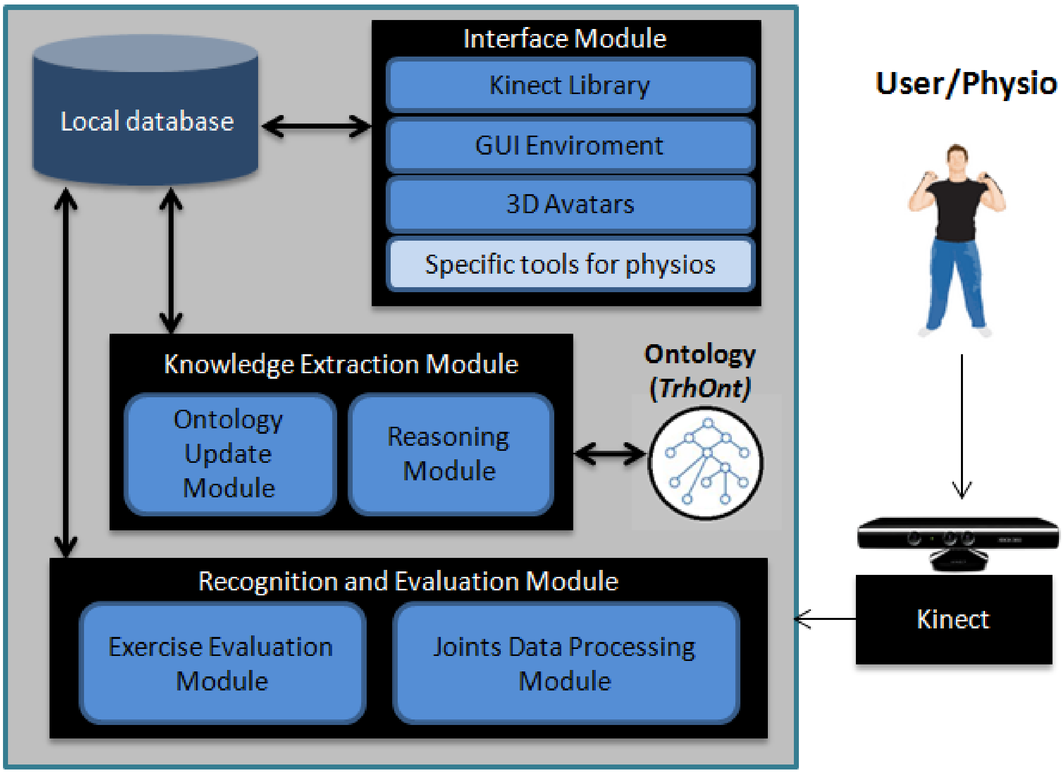


Fig. 4 - System architecture

2.2 KiReS workflow

The use of KiReS involves the performing of the activities shown in the UML activity diagram of Fig. 5, which are executed by three different actors: the physiotherapists, the users and the knowledge manager of the system. Some of these activities correspond to the therapy planning (pink) and others to the therapy execution and controlling (green).

With respect to the therapy planning, first of all, the physiotherapist makes an initial evaluation of the user, which includes what it is known as anamnesis. As a result of this evaluation some knowledge about the user is asserted in the Telerehabilitation Ontology (*TrhOnt*). After that, the physiotherapist assigns appropriate exercises to the user taking into account those recommended by *TrhOnt* (the ontology includes exercise descriptions, and the exact details of all joints and movements involved in the exercises are stored in the database, *KiReSdb*). If the physiotherapist wants to assign a particular exercise that does not exist yet, then the physiotherapist can create it by using the “Create New Exercise” activity.

Concerning the therapy execution and controlling process, once the exercises have been assigned, the user can perform them by using KiReS. Those exercises are monitored and the results are stored in *KiReSdb*. After the exercises have been performed and monitored, two different activities can take place: 1) the physiotherapist can make a user reevaluation in order to finish the rehabilitation process or to assign new exercises to the user; and 2) a knowledge extraction process can be performed in order to find new knowledge to add to the ontology.

For the implementation of the interfaces Unity 4 [102] was used and all the scripts that control the behavior of the interface were developed in C#. The avatars and the rest of the 3D models were modeled in 3Ds Max and exported to Unity. However, official Kinect drivers are not directly compatible with Unity, for this reason, some open source C# scripts [56] were used for interaction. This library provides basic functionality for Kinect for Windows in Unity.

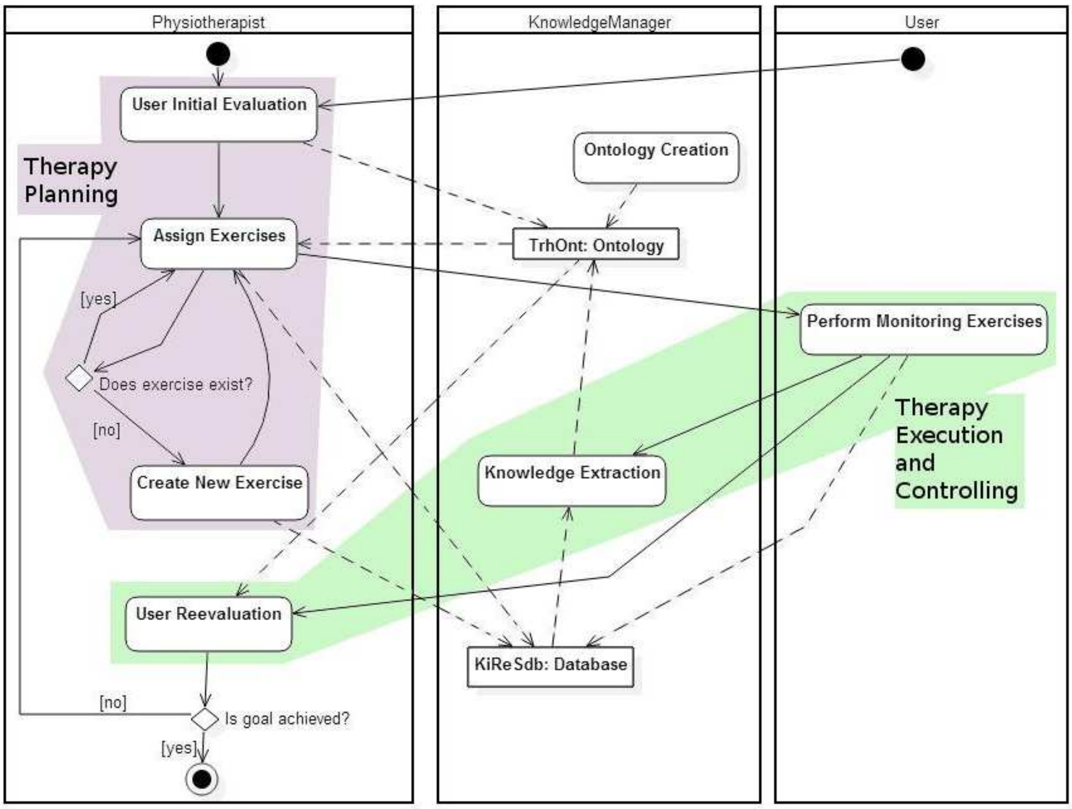


Fig. 5 - KiReS activity diagram

2.3 Therapy planning

One core artifact for the KiReS system is the telerehabilitation service ontology *TrhOnt*. It supports therapy planning by representing different kinds of knowledge and by providing some inference services. Creation of new exercises is also a part of the therapy planning process. KiReS offers an interface that provides assistance to define exercises and the *TrhOnt* guarantees coherent definitions. The ontology has been implemented using Protégé [84].

2.3.1 The telerehabilitation ontology (*TrhOnt*)

TrhOnt is an OWL ontology composed of four interrelated parts of knowledge (see Section 3.3.1). We have designed it as a service artifact; therefore, OWL reasoners' capabilities play a crucial role. In the following we explain more about each type of knowledge.

- *Patient knowledge:* This part consists of classes and properties for representing information such as personal and family data, goals, symptoms, results of physical examination, diagnoses, reported value in the Visual Analogue Scale (VAS) [74] and everything captured at the anamnesis.
- *Anatomy knowledge:* We have extracted a module from FMA-OWL [38] that is useful for the desired telerehabilitation process based on Kinect. Our module includes knowledge that can be relevant for a shoulder telerehabilitation process.
- *Movements and exercises knowledge:* Classes and properties have been defined to represent atomic movement and complex movement. Basically, a movement is characterized by its type, its associated joint and its amplitude (min and max range of movement). Furthermore exercise classes are defined as compositions of movements.
- *Experts' domain knowledge: TrhOnt* includes axioms that reflect specific knowledge about characteristics of recommended (and contraindicated) exercises depending on patient's state. This knowledge will be useful to the therapist during the "Assign Exercises" activity. Due to the information recorded, inference services applied on expert's domain knowledge are able to offer a list of recommended/contraindicated exercises for that patient.

The *TrhOnt* ontology takes part in the activities that evaluate and reevaluate users, the activity that assigns exercises to users and in the knowledge extraction activity.

2.3.2 Creation of new exercises

KiReS offers an interface for the physiotherapist that provides assistance to create exercises step by step, this way it is guaranteed that the exercise structure is respected and our recognition algorithm is able to evaluate them.

A posture is the simplest element of an exercise and therefore necessary for the definition of any other structure. The physiotherapist performs the posture in front of the system and records it (see Fig. 6). Then, a recording player tool allows the physiotherapist to select frame by frame which postures to store from the recording. Before storing postures, the posture recognition algorithm analyzes them in order to guarantee that they are similar enough. This similarity verification avoids adding very different postures with the same name and, at the same time, with well labeled postures the accuracy of the recognition algorithm is higher.

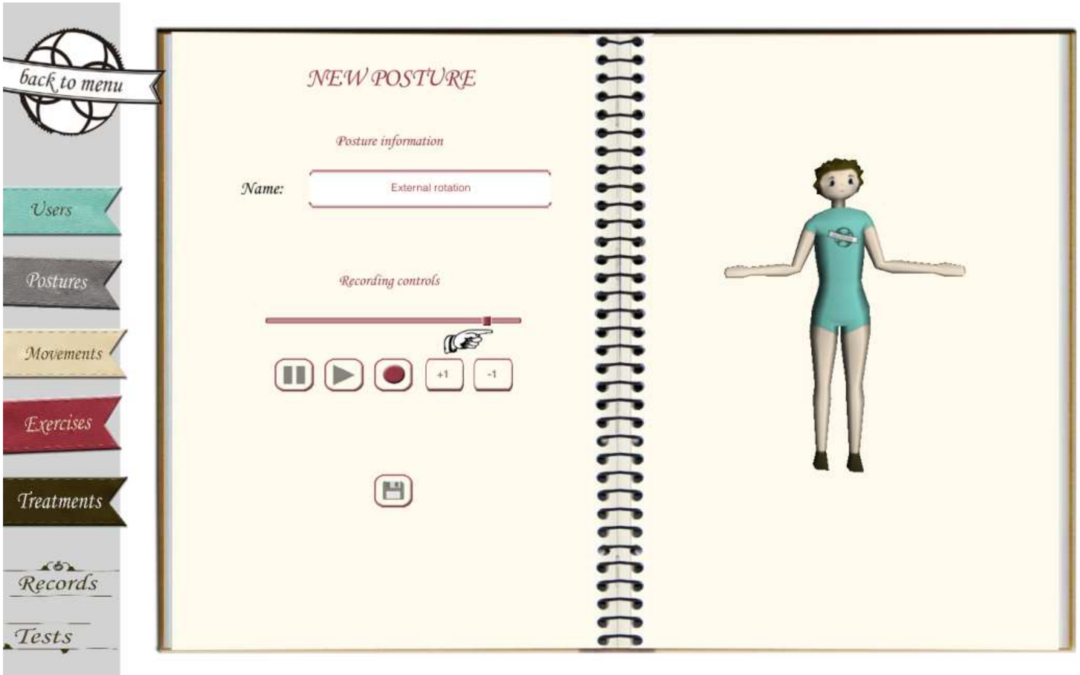


Fig. 6 - Posture edition

Movements have associated a name to identify them and are defined with two postures (initial and final) and with the recording of the transition between those postures (Fig. 7). Once both postures are selected, the system analyzes them. The relevant joints that best represent the transition from initial posture to final posture are selected and these joints are recorded and stored. Movement recording makes use of the same features as posture recording. The physiotherapist selects the movement to record and visualizes the initial and final postures of the movement. The posture recognition algorithm checks when the therapist makes both the initial and final posture and in the meantime the trajectories of the relevant joints are recorded. After reaching the final posture the recording player tool shows the movement and the therapist can replay it and decide whether to store it in the KiReS database or repeat the recording. The information concerning the name, the initial and final postures, the type, the joint of the movement and the range of motion involved is added to the ontology to allow reasoning over movements.

Lastly, exercises are defined by assigning movements to them. Simple exercises can consist of just one movement but complex exercises are a combination of basic movements, which create a sequence of movements. The only restriction when combining movements is that the final posture of a movement must match the initial posture of the next one. The exercise creation interface allows the therapist to define the composition of an exercise. It shows a form to fulfill data about the exercise and two lists with the movements assigned to that exercise and with the available movements to add. Once stored in the system (in the database and in the ontology) the exercise will be available to be added to a therapy session.

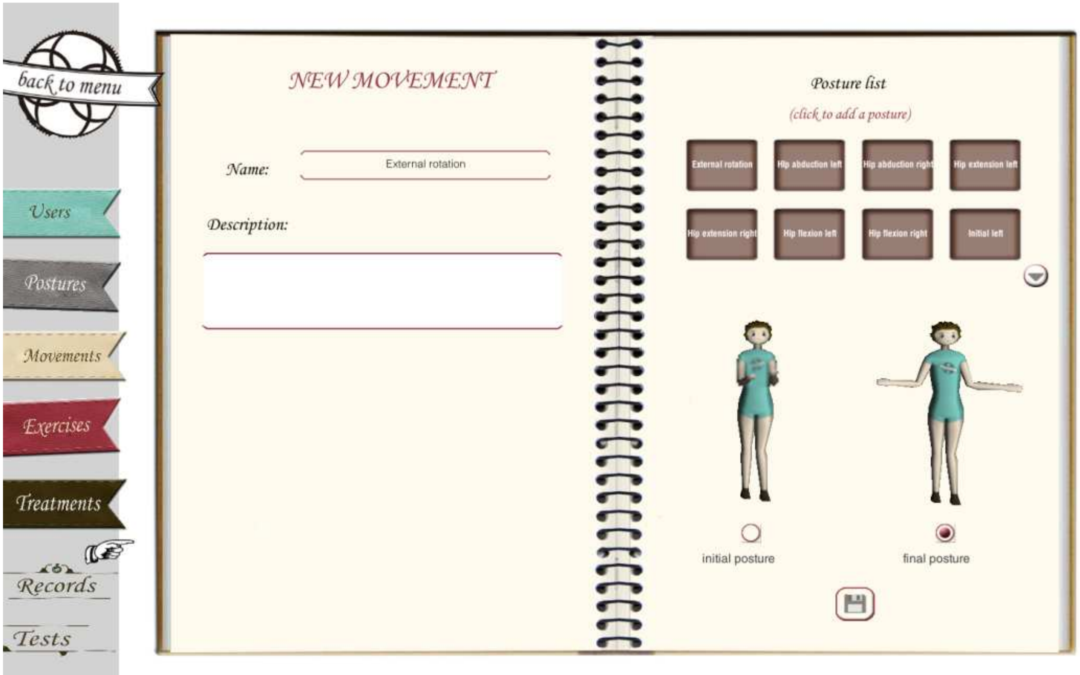


Fig. 7 - Movement definition

2.3.3 Test management

Performance evaluation is an important factor in a therapy session. In the specialized literature many user-oriented tests can be found. This kind of test is designed to be answered by the user after ending a therapy session. The answers of the user provide qualitative and quantitative information about his/her state. Answers to questions about daily life or pain suffered can provide useful information as a complement to the objective information that is automatically retrieved during exercise execution. Since these tests are widely used in physiotherapy sessions we decided to incorporate the functionality that supports them in KiReS.

Therefore, KiReS includes a tool with which the physiotherapist can create and manage these tests. The physiotherapist defines the questions in the test, the answers those questions and the score for each of the possible answers. Our proposal includes the option of adding two types of subjective evaluation tests, auto-tests (Fig. 8) and Visual Analogue Scale (VAS) (Fig. 9). Users may answer these tests after they end the corresponding sessions in order to provide KiReS with subjective information (complimentary to objective information obtained from exercise executions).

The auto-test interface is oriented to create, manage and evaluate auto tests. These auto tests include questions about different aspect of user's daily life and the possible answers are valued differently depending on their severity.

The tool to manage these tests lets the therapist define the questions of the test and the possible answers with their scores (see Fig. 8). By default, the tests are evaluated by adding the scores of the provided answers and giving a final result. But the tool allows the definition of the type of function to be applied to the scores, for example the system can count the number of answers with a certain score or give the result as a percentage depending on a fixed value. Once a test is defined, the therapist can assign it to a therapy, so that the user will have to answer the test after ending a session.

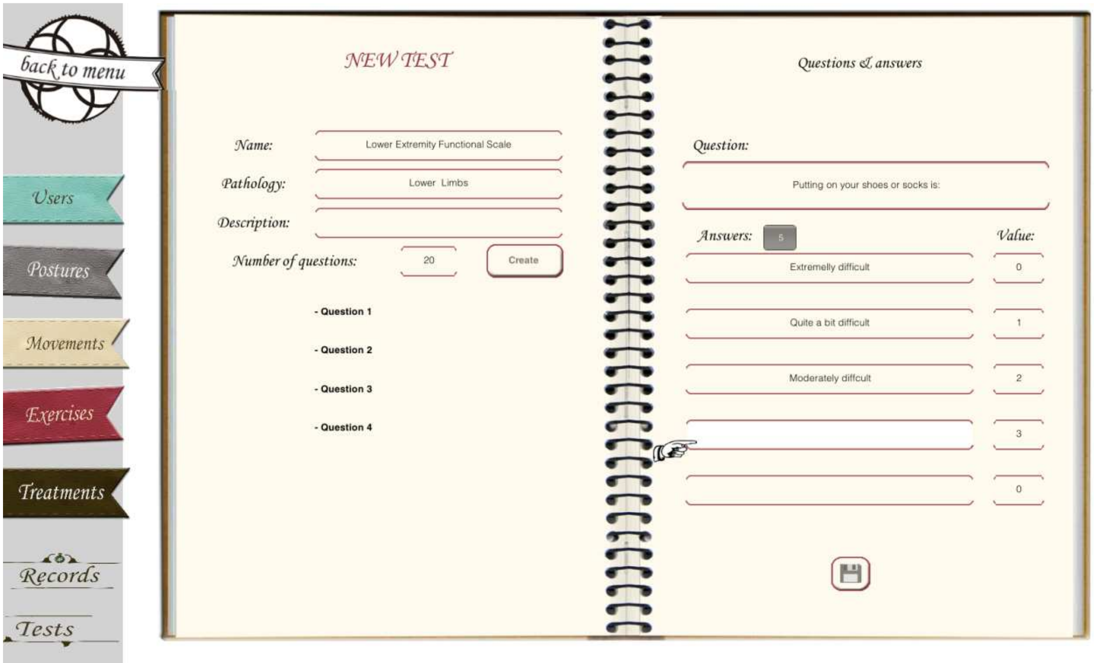


Fig. 8 - Auto-test creation

Another evaluation tool used in physiotherapy that we have incorporated to KiReS is the Visual Analogue Scale (VAS). The VAS is a technique used to measure subjective phenomena like pain. It is a self-reporting device consisting of a line of a predetermined length that separates extreme boundaries of the phenomenon being measured [74]. The user sees the image A, on which s/he marks a point on the line between the "no pain" label and the "worst pain ever" label (see Fig. 9). As in auto tests, the physiotherapist decides when the rest will be presented to the user. This data is incorporated to the ontology (see Section 3.3.1) and can be accessed by the physiotherapist for its analysis.

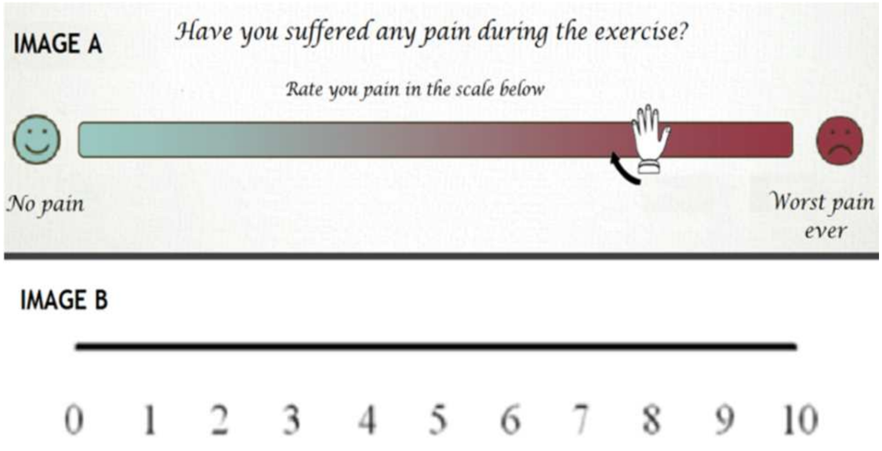


Fig. 9 - VAS example

2.4 Therapy execution and controlling

Users are monitored at the same time they are performing the exercises and all captured data are recorded in the KiReS' database. After that the physiotherapist can make a user reevaluation in order to finish the rehabilitation process or to assign new exercises to the user. Moreover, the knowledge extraction activity is performed in order to find new knowledge to add to the *TrhOnt* ontology.

2.4.1 Performing exercises

When users are performing exercises at home the interface must meet two requirements. It has to be easy to understand and at the same time attractive enough to encourage users to participate in therapy. The exercise interface of KiReS presents two 3D avatars that guide the user (see Fig. 10). The avatar on the right shows the movements of the user in real time, while the avatar on the left acts as an instructor, showing the exercise the user has to do. This avatar can show the posture or the movement the user has to perform. When showing a movement the avatar makes the movement and waits a few seconds so that the user can perform it. After that time, the avatar redisplays the movement.

The four boxes below (see Fig. 10) provide information about the ongoing therapy session to the user. The two boxes on the right show the number of series and repetitions left[1]. When the user has done all the series the session is finished. The box on the left shows the name of the next posture the user has to reach. The box in the middle shows the "state" of the current movement, it is continuously updated by the

[1] A series is the list of exercises to be done on a session and the repetitions is the number of times an exercise has to be done in each series.

exercise recognition algorithm and it displays information to guide the user in real time. Besides, when the user is close to reaching a posture, the box indicates with a three level color scale (red, yellow and green) how close s/he is from reaching the posture. In the upper center of the screen there is a ribbon that shows the exercise as a list of postures that have to be reached in the current execution. This ribbon is updated as the user completes exercises to show in every moment how many are left. Under this ribbon a textual explanation of the exercise is displayed. When a session is finished a new screen shows the results of the session: the execution accuracy of all exercises execution, the time taken to finish the session and the final evaluation of the session.

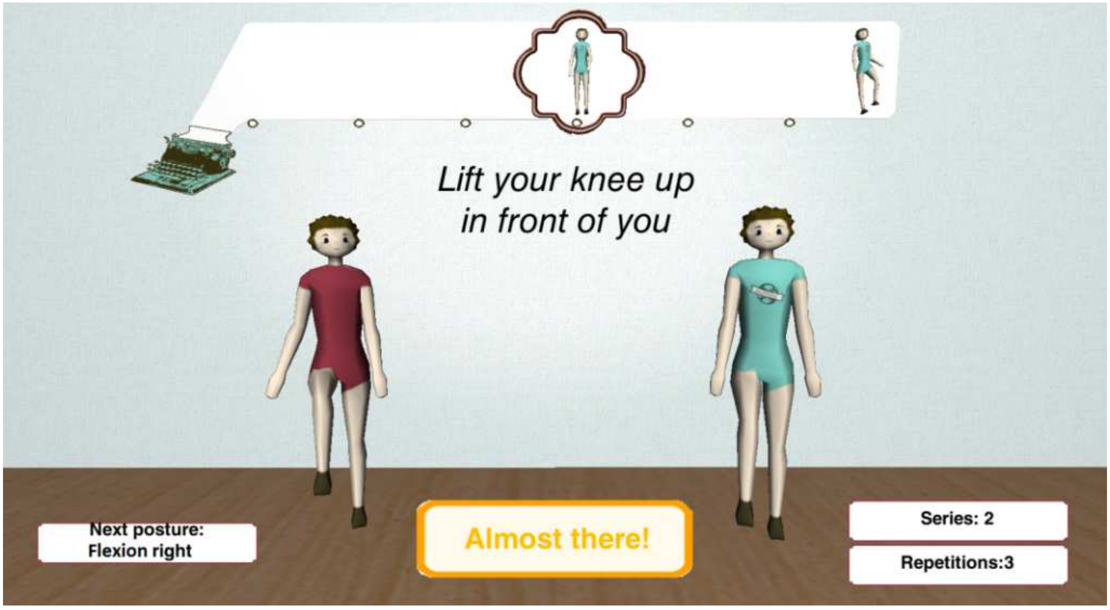


Fig. 10 - User exercise interface

In summary, the avatars and the informative boxes provide information to the user. This way, the system empowers and keeps the user aware of his/her therapy, but also provides a game-like immersive experience that motivates and makes the therapy more enjoyable.

2.4.2 Exercise Monitoring

While the user is performing the exercises, the system evaluates them and sets if they have been properly executed by comparing the results obtained with the recorded reference data.

As mentioned in Section 2.3.2, exercises usually consist of series of movements. Each movement is composed of an initial posture, a final posture and the angular trajectories of the joints involved in the movement (the relevant joints). The details about exercise recognition and monitoring are presented in Section 3.1.

2.4.3 User Reevaluation

After the user has performed the exercises and the knowledge extraction process has been made, the physiotherapist must decide if the user has achieved the rehabilitation goals, or if new exercises must be assigned to the user. For that, the new extracted knowledge about user’s medical condition (obtained ROM, accuracy, speed…) will be available in the ontology ready to be checked by the physiotherapist.

Everything must be made as simple as possible, but not simpler.

Albert Einstein

CHAPTER 3

KIRES: COMPONENT TECHNICAL DETAILS AND SYSTEM VALIDATION

This chapter presents the components of KiReS and the system validation. In its sections it is presented: a) *the exercise recognition algorithm* designed for KiReS. A detailed description of each of the components of an exercise (postures, movements, trajectories) is given and the recognition process for exercises is explained. b) The main features of *KinectRTC*, a framework based on WebRTC and Kinect, which allows for real-time communication and interaction between a physiotherapist and a patient. c) *TrhOnt*, a service ontology, which can assist physiotherapists in their daily tasks via reasoning supported by semantic technology. The ontology fulfills the purpose of providing a reference model for the representation of the physiotherapy-related information that is needed for the whole physiotherapy treatment of a patient. And finally, we present the *trials* that took place to test the recognition algorithm that KiReS uses and to validate KiReS with real patients who have had a total hip replacement.

3.1 Exercise recognition

In this section, we present the exercise recognition algorithm designed for KiReS. The main objective of this algorithm is the description, recognition and evaluation of those exercises performed in front of Kinect.

The novel contributions of the algorithm are:

- A descriptor that encodes body postures in a low dimensionality data structure.
- A posture classification method that allows comparing posture descriptors and assessing their similarity.
- An exercise recognition method that rates exercise executions through a 3-step process that takes into account body postures and movements.
- The evaluation of the algorithm to estimate its performance and establish the best suiting parameters.

Finally, the proposed algorithm has been validated in a real scenario with shoulder rehabilitation patients.

3.1.1 The descriptor of postures

As it has been stated before, the data obtained by Kinect allow for viewing a scene in three dimensions and provide information about users' position and joints. Kinect provides a skeleton structure in which each node is a joint in the body (see

Fig. 11). This skeleton gives access to the information of 20 body joints[2] including the joint coordinates in 3D, joint orientations and tracking states. Using the joint coordinates a descriptor is created that can be used to represent and unequivocally identify a body posture.

These joint coordinates are referenced in a coordinate system (axes X, Y and Z) whose origin is at the center of the plane parallel to the captured image and intersecting with the Kinect camera. The coordinates obtained from Kinect are preprocessed in order to translate them to another coordinate system whose origin is at the hip center of the user so that relative position between the camera and the user does not influence the exercise recognition. Those translated coordinates are used to calculate the following three types of measurements:

1) *Relative positions of some parts of the body in the Z axis.* A volume around the user is defined by two values, a minimum and a maximum distance in the Z axis, and two binary features for each joint are generated: one that takes the value 1 or 0 depending on whether the Z coordinate of a joint is above the minimum, and the other one that takes the value 1 or 0 depending on whether the Z coordinate of a joint is below the maximum.

2) *Angles between joints.* They are the angles between the lines formed by two joints, relative to the origin of coordinates located at the first one of them.

3) *Angles between limbs.* They are the angles between two limbs connected by a joint.

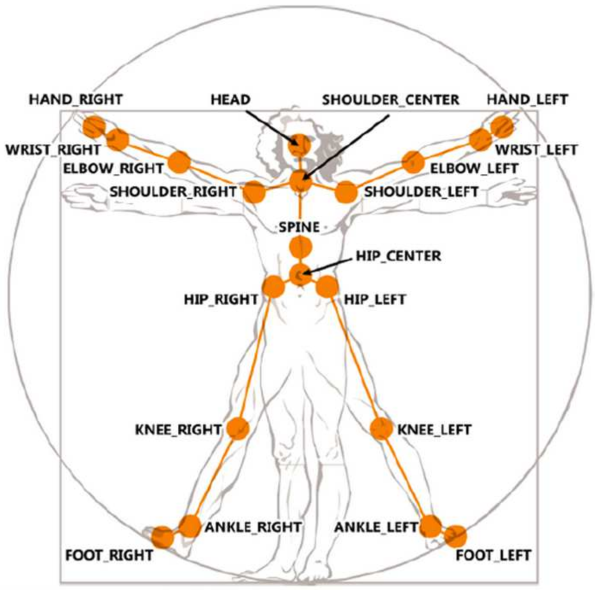


Fig. 11 - Kinect's skeleton model

[2] The first Kinect provides 20 joints; Kinect 2 now provides 23 joints.

The values are represented in a posture descriptor that we defined and which reduces significantly the dimensionality of the data. This descriptor is a simplified representation of a body posture; it encodes a set of data and still encompasses sufficient information for the recognition process as we show in Section 3.1.2. The posture descriptor has a total of 30 features (see Table 1), divided in two distinct parts, 18 binary features (from 1 to 18) that provide information about the relative position in 3D of some joints (neck, hands, shoulders, knees and feet) and 12 features that represent the angles formed by the different parts of the body projected in the frontal plane (XY) (from 20 to 24 and from 26 to 30) and in the lateral plane (XZ) (19 and 25).

Table 1 - Variables of the posture descriptor

BINARY	1	2	3	4	5	6
	NeckMin	NeckMax	RHandMin	RHandMax	LHandMin	LHandMax
	7	8	9	10	11	12
	RShoulMin	RShoulMax	LShoulMin	LShoulMax	RKneeMin	RKneeMax
	13	14	15	16	17	18
	LKneeMin	LKneeMax	RFootMin	RFootMax	LFootMin	LFootMax
ANGLES	19	20	21	22	23	24
	NeckZ	NeckX	RElbow	LElbow	RShoul	LShoul
	25	26	27	28	29	30
	ColmZ	ColmX	RThigh	LThigh	RLeg	LLeg

Therefore, we transform Kinect data from a representation of 20 3D points to a descriptor of 30 features. It is clear that if we reduce the dimensionality of the data for our posture descriptor there is a loss of information compared to Kinect's skeleton. However, the binary values in the descriptor incorporate the depth information that the angles don't provide. This information about depth is useful for the recognition of some postures that are not performed parallel to the Kinect plane.

3.1.2 Posture classification method

The process of capturing and processing a posture to create its descriptor is the first step in posture recognition. Then, classification is made by comparing the generated descriptor with previously annotated posture descriptors. In order to compare two posture descriptors D_i and D_j, a similarity measurement, $sim(D_i, D_j)$, based on the distance between them is used:

$$sim(D_i, D_j) = angDif(D_i, D_j) * \left(1 + binDist(D_i, D_j)\right) \quad (3.1)$$

As mentioned before, the descriptor is composed of two parts: on the one hand, a set of 18 binary features and, on the other hand, 12 angular measurements of body members. The two parts of the descriptor ($binDist(D_i, D_j)$ and $angDif(D_i, D_j)$) are evaluated independently, by using formulas based on the sum of absolute errors of their corresponding descriptor features:

$$binDist(D_i, D_j) = \sqrt[2]{\sum_{k=1}^{18} |D_i(k) - D_j(k)|} \quad (3.2)$$

$$angDif(D_i, D_j) = \sum_{k=19}^{30} |D_i(k) - D_j(k)| \quad (3.3)$$

where D_x *(k)* is the feature *k* of descriptor D_x, and the results are combined to obtain a measurement of similarity between postures (see right part of equation (3.1)).

To classify a new posture descriptor, a search is applied sequentially on the set of all previously recorded and annotated posture descriptors. If the distance between the posture descriptor to be classified and the annotated posture descriptors is less than a threshold value pth_0, then the corresponding class is assigned[3]. If there is none, then the posture is classified as “unknown” (see Method 1).

It is quite obvious that the lower the threshold value pth_0, the greater the similarity between the compared posture descriptors must be. In the event that pth_0 were 0, then the user must perform a posture that is exactly the same as one that has been previously recorded in order to be classified as that. However, it must be noticed that there are different descriptors annotated with the same posture class. Therefore, using a threshold pth_0=0 may be not appropriate when the posture descriptor performed is not exactly equal to any of the recorded ones, but it is definitely of that posture. On the contrary, greater values for the threshold would make a posture descriptor be misclassified. In section 3.1.3.7 we show which is the optimal value obtained for this trade-off value that is pth_0.

[3] When different posture classes could be assigned, the one with the smallest distance between the posture descriptor to classify and the annotated posture descriptor is in fact assigned.

```
Method 1: Posture classification
Input
nDesc= New posture descriptor
discList= The list of annotated posture descriptor
minSim= Min similarity value (initially 999)
thr= Threshold value
Output
class= Descriptor's class (initially "Unknown")
Procedure
foreach Descriptor d in descList
  sim=dist(nDesc, d)
  if(minSim>sim)
        minSim=sim;
        class= d.class;
  end if
end foreach
```

3.1.3 Exercise recognition method

In rehabilitation therapies, exercises are usually defined using tables that contain exercises with drawings on which the limbs of the body that should be exercised and what movements should be performed are indicated. The definition of the exercises in our system is based on this way of working in order to develop a methodology as close as possible to that followed by physiotherapists. Exercises consist of a series of movements and each movement is composed of an initial posture, the trajectories of the joints involved in the movement, and a final posture (see Fig. 12).

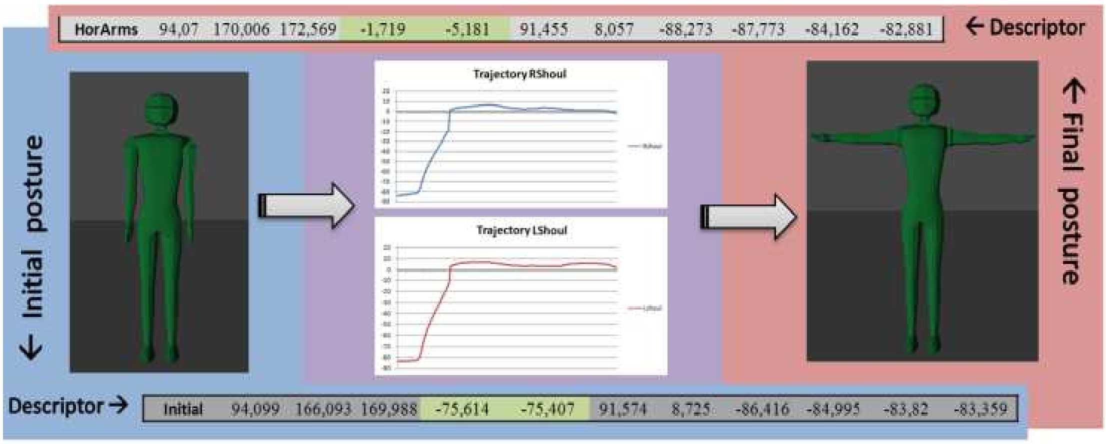


Fig. 12 - Structure of a movement

Both, the initial posture and the final posture of a movement are identified with their respective posture descriptors. The movement between the initial and final posture is represented by sequences of angular values taken from the limbs that are in a different position from one posture to another (it is assumed that the limbs whose positions are equal in the initial and in the final postures do not move during the transition). The individual movements can be combined to compose more complicated exercises. These complex exercises are defined linking basic movements, creating a sequence of movements where the final posture of a movement matches the initial posture of the next one. When a user is performing exercises, the exercise recognition algorithm analyzes in three stages the elements which describe a movement (initial posture, a final posture and the trajectories of the most relevant joints) to evaluate and rate the performance.

3.1.3.1 Identification of the initial posture

When starting an exercise the system waits for the user to perform the initial posture of that exercise (initial posture of the first movement in that exercise). The posture recognition method checks the user's current posture comparing with the expected posture descriptors until it identifies the starting posture of the movement. These checks are performed in real time at a rate of 30 Hz which is the frequency with which Kinect provides data. When the initial posture is identified the system starts trajectory recognition.

3.1.3.2 Trajectory recognition in real time

During the recognition of the trajectory, the trajectory performed by the user is compared to the set of trajectories stored for that movement. If the distance is below a certain threshold the path of motion is correct (see Section 3.1.3.5). If for any of the variables the method detects that the executed movement is not the expected one, the system indicates the user which limb position must be corrected. The data is checked every 10 frames, we noticed that checking trajectories more frequently was inefficient because differences in the trajectories were not relevant at higher rates.

3.1.3.3 Identification of the final posture

While analyzing the trajectories, the exercise recognition method also checks the posture of the user. When the final posture is identified the movement is finished. If an exercise has more movements the algorithm goes back to the first step and continues exercise recognition checking the initial posture of the next movement.

Identifying the final posture has a peculiarity given the context of rehabilitation. In some stages of therapy what is expected from the user is to try to reach that position or, at least, to make the physical effort to reach it. Assigning adequate exercises is the physiotherapist's decision but we also considered a "reach and hold" objective for the patient. Thus, the method adapts the threshold depending on the time spent performing the movement. The initial threshold *pth0* is multiplied by a flexibility factor *ff* that makes the algorithm be less rigid in posture classification (see Section 0).

3.1.3.4 Exercise rating

When the user has completed a movement, the method analyzes the result and rates the overall performance. This rate r is calculated from the values v_i obtained for each relevant limb i (as explained in section 3.1.3.5) with the following formula:

$$r = \sqrt[2]{{v_1}^2 + {v_2}^2 + \cdots + {v_n}^2} \quad (3.4)$$

where n is the total number of relevant limbs analyzed. Although the flexibility factor *ff* does not appear explicitly in the formula, the rate r takes it into consideration implicitly, because v_i values will be greater when the final posture is not performed exactly. Finally, the overall exercise rating is the average of the r rates of all the movements that compose the exercise.

3.1.3.5 Transition between postures

The transition movement between the initial and final postures is represented by a data series of the angular trajectories of the limbs that are in a different position (it is assumed that the limbs whose positions are equal in the initial and in the final postures do not move during the transition). The analysis of the relevant variables is performed using a variant of the Dynamic Time Warping (DTW) algorithm (please refer to [94] for detailed information on DTW). It is applied on a set of trajectories to obtain the distance between the newly introduced and the known ones. Although other alternative techniques such as Hidden Markov Models (HMM) have been extensively used for gesture recognition, we chose the DTW technique after analyzing some works that compare their behavior [11,26,108] and finding that it allows us to: 1) deal with a much smaller training set [11]; 2) not have to re-train a model after a new movement is recorded, an advantage that makes the recording of exercises clearer, simpler and faster for the physiotherapist; and 3) analyze the data in real-time as its performance is high enough [108] for the analysis of exercises.

During the recognition, the trajectory of each relevant limb i involved in the movement is compared to the trajectory of the same limb stored for that movement and a similarity value v_i is obtained based on distances between them. If the distance is less than a threshold value *trth* the trajectory path is considered to be correct, and incorrect in opposite case.

Another important aspect here related with the goal of recognizing trajectories in real-time is the frequency of the trajectory recognition or, in other words, how often this comparison among performed and stored trajectories has to be executed. Taking into account that trajectory recognition in real-time is a requirement, it is not possible to compare the completely performed and stored trajectories only once at the end. For that reason, we also introduced partial trajectory recognition analysis. Therefore, our trajectory recognition method periodically compares for each limb, the trajectory path performed up to that moment by the user with the corresponding stored trajectory. And, as the user may have not finished the movement completely, a last comparison with the complete stored trajectory also has to be executed. In summary, a two-phase analysis takes place: an analysis of partial trajectories and an analysis of the complete trajectory. The trajectory is classified as incorrect when either some[4] partial trajectories or the complete one is incorrect, and as correct in opposite case. In section 3.1.3.8 we explain how we have obtained the *trth* trade-off value. Notice that this method is able to detect incorrect trajectories in real-time and can indicate to the user which limb position must be corrected.

3.1.3.6 Algorithm testing set-up

The datasets created to validate the algorithm contain body postures and recordings of some rehabilitation exercises. In particular, the recorded exercises are part of two therapy protocols. One is oriented to cervical disorders and the other one is oriented to shoulder disorders. These protocols describe with detail the rehabilitation phases and exercises adequate for each treatment, we used six exercises to test our algorithm[5].

Five healthy volunteers (3 male and 2 female) with ages from 25 to 58 took part in the recording of the above mentioned exercises. Using the resulting data, posture descriptors were annotated manually with each corresponding posture class (seven known posture classes and another one for unknown postures). Those annotated descriptors constituted the test dataset of 4500 different posture descriptors. In addition to this dataset, a training set was created which has 45 posture descriptors labeled with the previous 7 known classes. Table 2 shows the distribution of the posture descriptors on each of the datasets.

[4] If the recognition method were too strict, then just one punctual incorrect partial trajectory would lead to classify it as incorrect. However, we think that is better to be more flexible and wait to see if the following ones are also incorrect or not.

[5] The specifications and the execution descriptions of the exercises can be found in http://bdi.si.ehu.es/bdi/members/david-anton/research-resources/

Table 2 - Training and test sets composition for postures

Label	Nº
Neutral	6
HeadLeft	5
HeadRight	5
RHandUpLeft	8
RHandDownLeft	8
RHandUpBack	8
TOTAL	45

Label	Nº
Unknown	1090
Neutral	1253
HeadLeft	248
HeadForward	326
RHandUpLeft	446
RHandDownLeft	346
RHandUpBack	454
TOTAL	4500

To measure the time performance we needed datasets with different sizes. We used six datasets with 45, 4500, 15000, 20000, 35000 and 45000 posture descriptors respectively in order to perform time measurement tests. The last four datasets are synthetic sets created by repeating the descriptors in the dataset with 4500 descriptors.

We also created two datasets to carry out the trajectory tests. One was used as training set that contained 32 correctly performed trajectories, and the other one was used as test set that contained 48 trajectories, 24 correct and 24 incorrect (see Table 3).

Table 3 - Training and test sets composition for trajectories

Label	Nº
ToHeadLeft (THL)	4
ToHeadRight (THR)	4
ToHeadForward (THF)	6
ToRHandUpLeft (TRHUL)	6
ToRHandDownLeft (TRHDL)	6
ToRHandUpBack (TRHUB)	6
TOTAL	32

Label	Corr	Incor
THL	4	4
THR	4	4
THF	4	4
TRHUL	4	4
TRHDL	4	4
TRHUB	4	4
	24	24

3.1.3.7 Posture threshold pth_0

As stated in Section 3.1.2, the optimal value for the pth_0 must be empirically found. A series of tests were conducted with threshold values between 5 and 50 to assess which of them gave the best results. The 4500 posture descriptors of the test set were classified with different threshold values. The results showed that the maximum is reached on threshold $pth_0 = 30$ with an accuracy of 91.9% and that with higher threshold values accuracy slowly decreases as shown in Fig. 13. As pth_0 is a trade-off value, then greater or lower values decrease accuracy, but in a different way: with greater values "unknown" posture descriptors are classified as known postures, but with lower values some of the known postures are classified as "unknown".

Fig. 13 - Descriptor classification accuracy depending on threshold

The confusion matrix in Table 4 provides more detailed information of these results for the optimal threshold value 30. Each element indicates the number of times the posture of the row has been classified as the posture of the column. The posture descriptors labeled as "unknown" are mostly transitional, undefined postures that occur when moving from one known posture to another.

Table 4 - Posture confusion matrix for threshold 30

Posture	Unk	Neu	HL	HR	HF	RHUL	RHDL	RHDA	Total
Unknown (Unk)	802	165	20	18	34	9	29	13	1090
Neutral (Neu)	29	1223	0	1	0	0	0	0	1253
HeadLeft (HL)	0	0	248	0	0	0	0	0	248
HeadRight (HR)	2	0	0	335	0	0	0	0	337
HeadForward (HF)	0	0	0	0	326	0	0	0	326
RHandUpLeft (RHUL)	33	0	0	0	0	413	0	0	446
RHandDownLeft (RHDL)	5	0	0	0	0	0	341	0	346
RHandUpBack(RHUB)	5	0	0	0	0	0	0	449	454

Notice that most classification errors for unknown postures are produced because they are classified as "neutral" postures. The "neutral" posture is present in all the exercises analyzed, making the transition to it very common.

The optimal threshold value found for the posture evaluation was 30 but this value can be adjusted to increase or decrease the sensitivity of the system. This threshold can serve as a mechanism to control the difficulty of the exercises, as the algorithm would be more restrictive if the value was lower, or less restrictive if it was higher, when classifying a posture as valid. Testing the systems in a real scenario lead as to establish flexibility factor that changes the threshold value depending on the users physical and medical circumstances (see 3.1.3)

3.1.3.8 Trajectory threshold *trth*

We calculated the trajectory threshold using a similar procedure to the one used for the posture threshold. A series of tests were conducted with threshold values between 1 and 15. The 48 trajectories of the test set were classified with different threshold values. The results showed that the maximum is reached on threshold *trth* = 10 with an accuracy of 93.75%, as shown in Fig. 14. With higher threshold values the accuracy decreases because more incorrect trajectories are classified as correct.

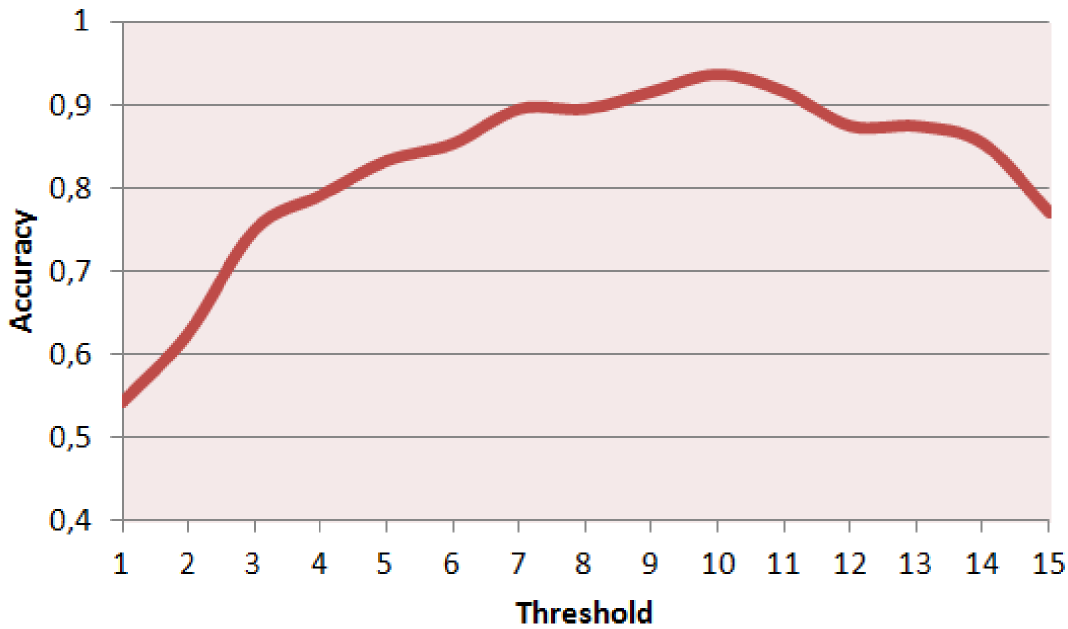


Fig. 14 - Trajectory classification accuracy depending on threshold

Nevertheless, as mentioned in Section 3.1.3.5, a trajectory is classified as correct or incorrect after applying a two phase analysis: a partial trajectory analysis and a complete trajectory analysis. In Table 5, we show the accuracy results obtained after applying the partial trajectory analysis using threshold *trth* = 10 (where global accuracy is 89.58%). It´s important to remember that trajectories classified as incorrect during the partial trajectory analysis are definitely[6] classified as "incorrect".

Table 5 - Partial trajectory analysis accuracy

	Ident. as correct	Ident. as incorrect
Correct trajectories	91.67%	8.33%
Incorrect trajectories	12.50%	87.50%

The trajectories classified as "correct" by using the partial trajectory analysis do still have to pass the complete trajectory analysis. After that, as can be seen in Table 6 all the correct trajectories are again (and definitely) classified as correct by the complete trajectory analysis, and 66.67% of the remaining incorrect ones are now well classified.

Table 6 - Complete trajectory analysis accuracy

	Ident. as correct	Ident. as incorrect
Correct trajectories	100%	0%
Incorrect trajectories	33.33%	66.67%

In Table 7, we can see the overall trajectory analysis accuracy results corresponding to the combined method of partial and complete trajectory analysis that provides a global accuracy of 93.75%, and in

Table 8 the detailed confusion matrix can be observed.

Table 7 - Overall trajectory analysis accuracy

	Ident. as correct	Ident. as incorrect
Correct trajectories	91.67%	8.33%
Incorrect trajectories	4.17%	95.83%

Table 8 - Trajectory confusion matrix for threshold *trth* = 10

	THL		THR		THF		TRHUL		TRHDL		TRHDA	
	Cor	**Inc**	**Cor**	**Inc**	**Cor**	**Inc**	**Cor**	**Inc**	**Cor**	**Inc**	**Cor**	**Inc**
Cor	4	0	4	0	4	0	4	0	3	1	3	1
Inc	0	4	0	4	0	4	0	4	0	4	1	3
Tot	4	4	4	4	4	4	4	4	3	5	4	4

[6] For this analysis, we have assumed that an incorrect partial trajectory has to be recognized as incorrect for at least 1.5 seconds in order to be definitely classified as incorrect.

3.1.3.9 Testing Real-time processing

Previously, we stated that the proposed algorithm should be able to process Kinect data in real-time in order to give feedback to the user as s/he was performing the exercise. Kinect provides 30 frames per second so the algorithm had to analyze 30 skeletons in less than a second to avoid execution delays. Posture analysis, which is done continuously, also implies generating the corresponding descriptors to compare with those already stored.

In order to obtain the processing time and establish how many postures can be processed in real-time, we conducted some tests with different dataset sizes. The tests for time measurement involved loading six datasets with, 45, 4500, 15000, 20000, 35000 and 45000 posture descriptors respectively.

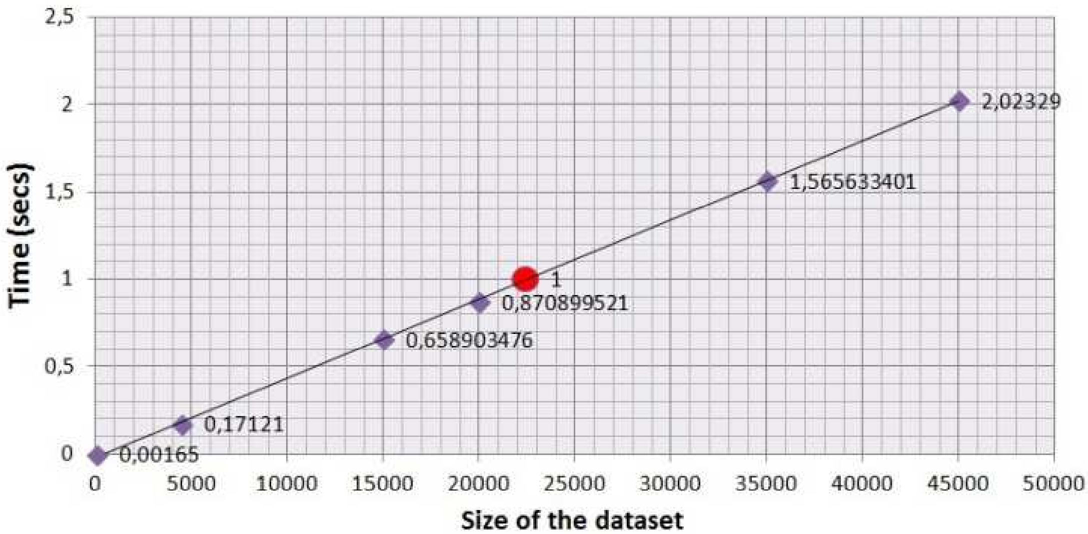


Fig. 15 - Average time to process 30 descriptors per dataset

In Fig. 15 we can observe the average time (in seconds) to process 30 unknown posture descriptors against each of the datasets. The linear regression fits the data obtained well, so it´s safe to say that the time required to process a posture descriptor increases linearly with the size of the dataset. According to these results the size limit beyond which it would not be feasible to process a dataset in real-time would be around 22000 posture descriptors[7], what ensures that it is possible to manage an adequate number of postures in this context. When trying to identify a particular posture it is reasonable to load samples of the expected posture and not the entire

[7] Notice that the equipment we used for the experiments is a standard PC with an Intel Xeon W3505 2.53 GHz processor and 4 GB of RAM.

dataset, so in practice, even if the dataset of postures has more than 22000 samples, it will not be necessary to process them all.

With respect to the real-time processing of trajectories the DTW algorithm is applied (see Section 3.1.3.5). According to Wang et al. [108] it is possible to process more than 10000 time series in real-time using DTW. In our case, we have just confirmed that it is possible to process the time-series of all the limbs with a frequency of 30 times per second (maximum quantity of data that Kinect can provide). However, through these experiments we also found that processing trajectories with DTW at a frequency greater than 3 times per second did not produce significant changes in the results of the trajectory analysis.

3.1.3.10 Validation with patients

After local validation with physiotherapy exercises performed by volunteers, we tested the recognition algorithm in a real environment. In this section, we present the evaluation of the algorithm and, in Section 3.4, we present detailed information about the set-up and the results of the patients. With the collaboration of Matia Foundation, the system was tested with 15 patients that suffered from shoulder disorders in two trials that took place in a rehabilitation center in Donostia-San Sebastian. A physiotherapist recorded a set of exercises to be executed. The recorded movements plus the reversed version of them were the following: shoulder abduction (1–2), hands to mouth (3–4), shoulder extension (5–6), shoulder flexion (7–8), hands to head (9–10), and shoulder rotation (11–12). Upon arrival the participants were assigned some of the exercises depending on their physical state. The two trials were supervised continuously by physiotherapists that assessed the correct or incorrect execution of the exercises. Therefore, two datasets of annotated exercises were built. One dataset with physiotherapist's recordings that were considered the ground truth for our algorithm, and another dataset with executions of the patients (annotated as correct and incorrect). Once both datasets were built, the validation of the recognition algorithm was conducted. In the following paragraphs we present the accuracy results grouped by: a) movement; b) exercise and c) user.

The average recognition accuracy for movements was 95.16%. Out of the all of the correctly executed movements, 97.12% were recognized as correct, but the rate decreases to 86.91% when classifying incorrect movement as incorrect. Moreover, in Fig. 16 (graph on the left) we can observe that accuracy of Mov4 and Mov10 is 58.32% and 75% respectively. This is because Mov4 and Mov10 are influenced by their initial postures which require lifting the arms towards the head, and in these postures Kinect has difficulties finding joint positions and produces noise in the data. For all other movements the accuracy was above 85%

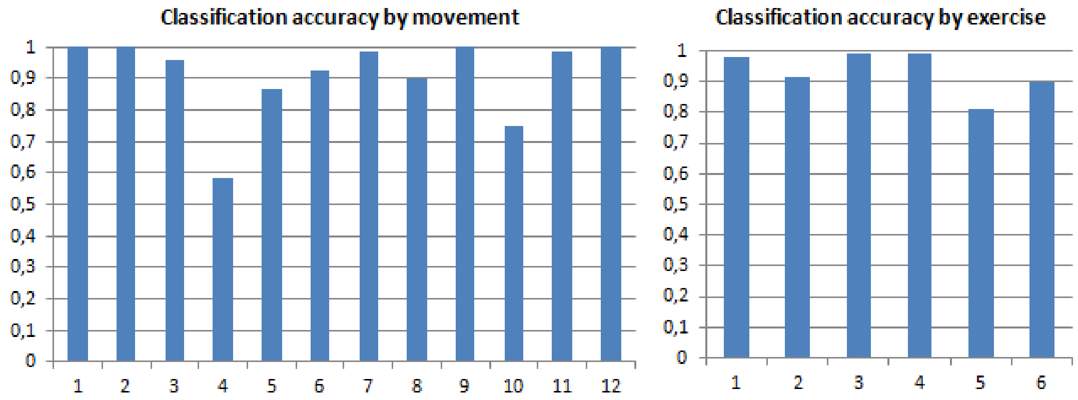


Fig. 16 - Recognition accuracy by movements and exercises

It can be observed that, for exercise 5 (see Fig. 16, graph on the right) the accuracy was significantly lower (81.23%), due to the fact that movements Mov4 and Mov10 are part of this exercise.

Finally, while analyzing the accuracy results for each user (in Fig. 17 we show the accuracy distribution for the users of the second trial) we found that, in general, the average accuracy was consistent with the previous results. However, there was an exception; user 13 (with a 75% accuracy) was wearing a loose blouse that made it difficult for Kinect to recognize joints correctly.

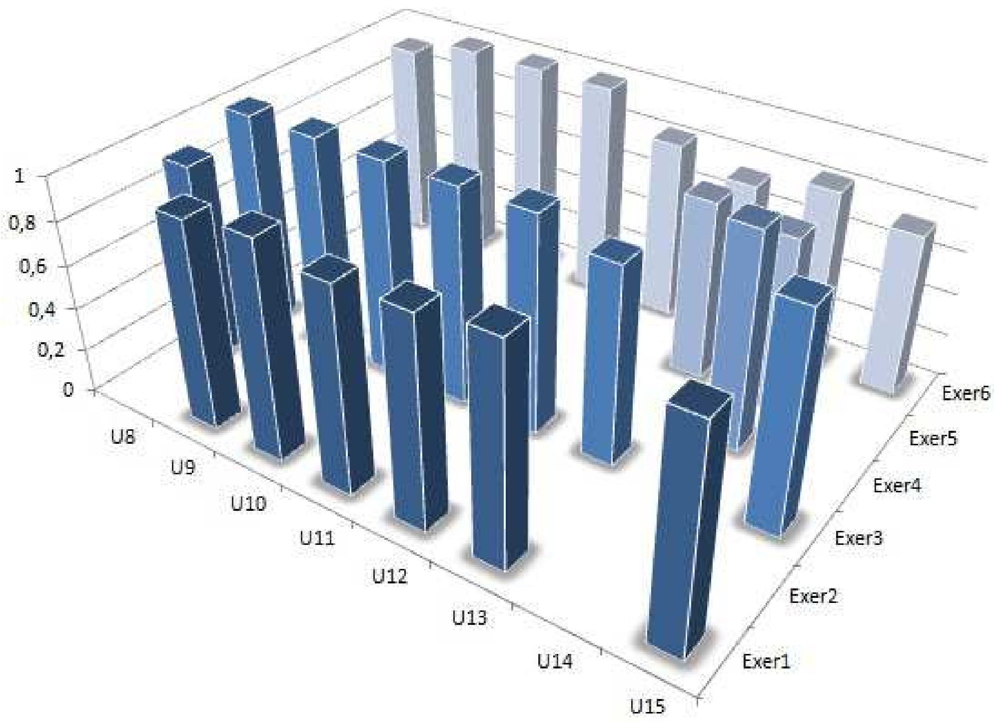


Fig. 17 - Exercise recognition accuracy by user

3.1.4 Tuning the exercise recognition method (The flexibility factor)

The flexibility factor (*ff*) was introduced to posture recognition as a means to give more flexibility to the physiotherapist when assigning exercises to patients. It is a factor applied to the threshold that establishes when two postures are similar enough to be considered the same. The initial threshold *pth0* is multiplied by a flexibility factor *ff* that makes the algorithm be less rigid in posture classification. That is to say that the new threshold value is $pth=pth_0*ff$. The flexibility factor *ff* is a function that depends on the time *t* spent performing a movement and the time t_r spent recording the movement, $ff = 1+\alpha \lfloor t/t_r \rfloor$ where α could be adjusted by the therapists ($\alpha = 0$ means no flexibility at all).

The exercise recognition algorithm used in KiReS has been tested and validated with exercises and various user trials. Nevertheless tests showed that a pure recognition-oriented algorithm sometimes doesn't match appropriately the needs in a real environment. While the algorithm has a high accuracy in recognizing postures and movements in a theoretical framework, in a real environment it might be considered very strict as patients differ from each other. During exercise sessions the physiotherapist might be more tolerant when considering an exercise correct depending on several factors that affect the patient. The flexibility factor (*ff*) that the algorithm includes can be adjusted and it makes possible to reduce the strictness of posture recognition by considering time. In practice this means that during the posture recognition phase of a posture the algorithm slowly increases the margin for a posture to be considered correct. This flexibility matches the 3 color stages described in Section 2.4.1. (e.g. If a patient reaches "yellow" and resists in that position for a while, eventually, the posture will be considered correct).

Moreover, testing the system in a real scenario showed that when physiotherapists assign exercises to a patient, their evaluation is frequently influenced by other factors such as age, functional objectives or postoperative time (post-op) (if the patients had surgery). We performed tests using the data obtained from the trials to assess the usefulness of incorporating these factors to the recognition algorithm. We considered the implementation of different methods for evaluating exercises and tested each method with threshold values from 10 to 90 varying the conditions applied to the pth_0. As a result we compared 8 different alternative methods in order to select the most adequate one:

- **Thr:** A fixed threshold value (*pth0*) to for the evaluation of the postures.
- **FF:** The flexibility factor that modifies the threshold depending on the time taken to reach a posture.
- **DTW:** The result of the DTW algorithm that analyzes exercises.

- **TOp:** A flexibility factor is applied but depending on the post-op time of the patient.
- **TOp+Dtw:** Combination of post-op flexibility and DTW.
- **FF+TOp:** Flexibility factor and post-op time.
- **FF+Dtw:** Flexibility factor and DTW.
- **FF+TOp+Dtw:** Flexibility factor, post-op time and DTW.

We calculated the accuracy for each of the evaluation methods mentioned (see Fig. 18) and then we worked with two statistical tests. The Friedman test [29] was applied to find out whether the evaluation methods used had any effect in the result. The Nemenyi test [23] allowed evaluating if noticeable differences existed between the performances of the methods. Friedman and post hoc Nemenyi tests are globally accepted statistical tools when several techniques are compared in different scenarios to assess the significance of the differences [23,34].

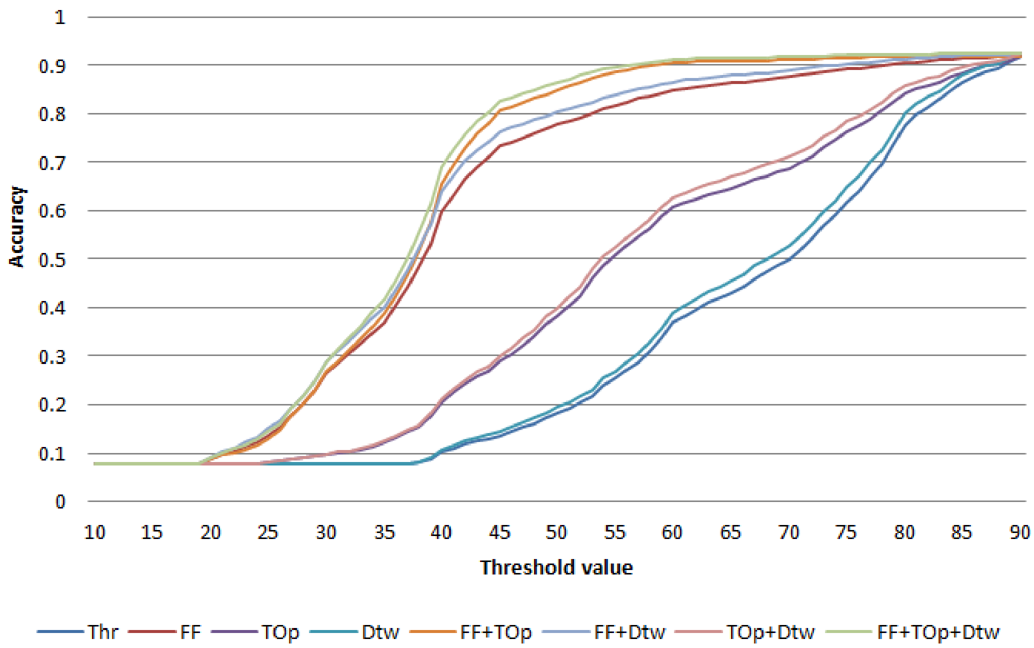


Fig. 18 - Accuracy of the different evaluation methods

3.1.4.1 Friedman test

Hypothesis: The method has no effect in the result of the evaluation (H_0).

Reject H_0 if: F≥critical value at α in X^2 distribution table with k-1 degrees of freedom, being (1 – α) the confidence level we want to achieve.

With 7 degrees of freedom X^2 critical value at $\alpha = 0.05$ is 14.07. In this case the H_0 is rejected for $\alpha=0.05$ as expected, since 500.528≥14.07. Friedman test concluded that significant differences exist among the evaluation methods (see Table 9a). Then a *post hoc* test such Nemenyi can be used to determine which method or methods differ significantly from the others.

a)

TEST STATISTICS	
N of elements(n)	81
N of methods (k)	8
Degrees of freedom	7
X^2 critical value at $\alpha = 0.05$	14.07
F	500.5279

b)

RANKS	
Thr	1.4074
FF	5.0926
TOp	3.0864
Dtw	2.1605
FF+TOp	6.3395
FF+Dtw	6.3765
TOp+Dtw	3.9383
FF+TOp+Dtw	7.5988

Table 9 - Relevant values for Friedman test

3.1.4.2 Nemenyi test

Hypothesis: The performance of methods *i* and *j* is not significantly different (H_0).

Reject H_0 if: the difference in their corresponding average ranks is at least the Critical Difference (CD).

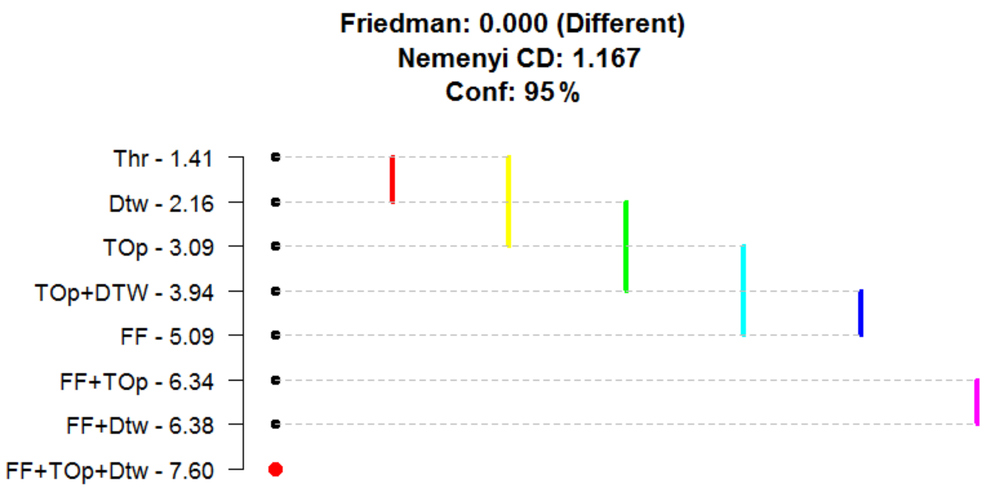


Fig. 19 - Pair-wise comparison of the evaluation methods

At a level of confidence of 95% (this is $\alpha = 0.05$) we get a critical difference, CD=1.167. Mean ranking for each evaluation method is indicated in Table 9b. H_0 is rejected for those pairs whose difference in mean ranks is at least the critical difference. Thus, two evaluation methods that are connected imply that there is not enough evidence to assume that their performance is significantly different (see Fig.

19). As *FF+TOp+Dtw* has the best rank and it is not connected to any other evaluation methods, the test shows that as this level of confidence there is enough evidence to conclude that *FF+TOp+Dtw* outperforms every other evaluation method.

3.2 Real-time communication

In this section, we present an implementation of WebRTC for real-time communication using Kinect. The objective of KinectRTC framework is to achieve real-time interaction between a physiotherapist and a patient inside a virtual environment. The novel contributions of KinectRTC are:

- A framework, based on WebRTC and Kinect, which allows for real-time interaction between a physiotherapist and a patient inside a virtual environment, while providing quantitative information on patient's movement.
- An implementation of WebRTC that facilitates stable and secure transmission of video, audio and Kinect data (i.e., camera parameters, skeleton data, and depth image) in real-time between two peers.
- The integration of KinectRTC in two existing research telerehabilitation platforms such as Tele-MFAsT or KiReS.

Furthermore KinectRTC has been validated in remote sessions between UC Davis and UC Berkeley and between University of the Basque Country, Spain and UC Berkeley, US.

3.2.1 WebRTC

Web Real-Time Communication (WebRTC) is a collection of standards, protocols, and APIs, the combination of which enables peer-to-peer audio, video, and data sharing between peers in real-time [5,65]. WebRTC has two different layers, WebRTC C++ API for browser developers or native RTC applications developers and a Web API for Web Application developers [51]. To acquire and communicate streaming data, WebRTC implements the following APIs:

PeerConnection (sending and receiving media) allows the direct communication between users (P2P). To open a connection and have a signaling negotiation, it is necessary to establish a signaling channel.

MediaStream (camera and microphone access) is an abstract representation of an audio and video data stream. This stream can be used to show, save and send its content from peer to peer.

DataChannel (sending non-media data direct between peers) is a bidirectional data stream for peer-to-peer connections. Data transmitted via DataChannel can be either UTF-8-encoded application data (ASCII) or binary data.

3.2.1.1 Voice and Video Engines

Enabling a rich teleconferencing experience requires an application to be able to access the system hardware to capture both audio and video. However, raw audio and video streams are not enough on their own: each stream must be processed to enhance quality, must be synchronized, and the output bit rate must be adjusted to the continuously fluctuating bandwidth and latency between the clients.

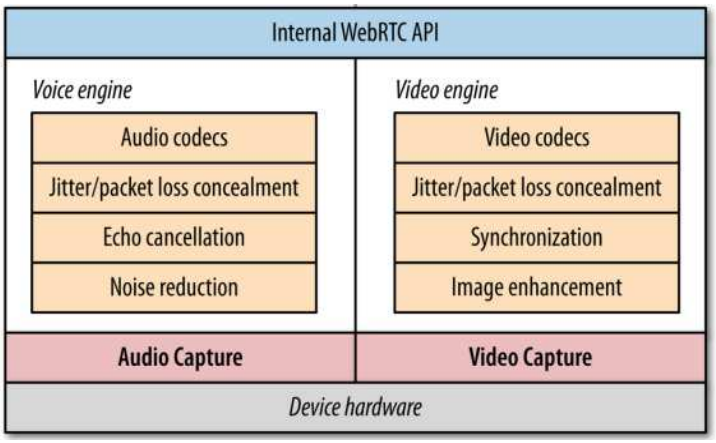


Fig. 20 - WebRTC internal API

WebRTC incorporates fully featured audio and video engines that take care of encoding and decoding with all the signal processing, such as echo cancellation, noise reduction or image enhancement (see Fig. 20). On the receiving end, the process is reversed, and the client must decode the streams in real-time and be able to adjust to network jitter and latency delays [42].

3.2.1.2 Data Channels

Data channels are designed to transfer data directly from one peer to another. They work with the PeerConnection API, which enables peer to peer connectivity. The transport properties of a data channel, such as order delivery settings and reliability mode, are options configurable by the peer as the channel is created. As encryption is mandatory for all WebRTC components, data channels are secured with Datagram Transport Layer Security (DTLS). DTLS is a derivative of SSL, meaning that data will be as secure as using any standard SSL based connection [3,42].

3.2.2 KinectRTC

The KinectRTC framework integrates WebRTC to stream 3D video (RGB+depth), audio and skeletal data retrieved from Kinect. The process requires a server where clients connect to manage the peers. The signaling process begins with the registration of a peer in the server, at the same time, when a client is connected to the server it receives the list of the available peers. Then a client chooses one of the peers and the connection is negotiated with it. In order for the WebRTC application to establish a direct connection, the clients exchange information to coordinate communication through a signaling process (see Fig. 21). Peers negotiate the following properties [111] to establish a connection:

- Session control messages used to open or close communication and error messages.
- Media metadata such as codecs and codec settings, bandwidth and media types.
- Key data to establish secure connections.
- Network data, such as a host's IP address and port as seen by the outside world.

The key information that needs to be exchanged is the multimedia session description, which specifies the necessary transport and media configuration information necessary to establish the media plane.

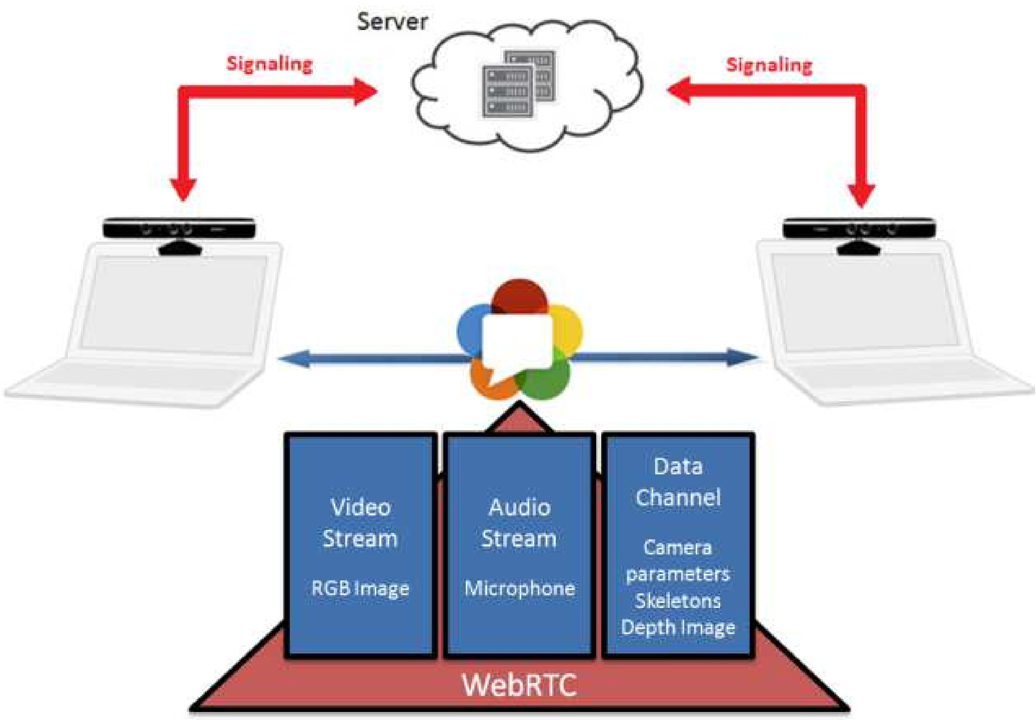


Fig. 21 - KinectRTC architecture

It is worth noting that the WebRTC standards allow for any codec to be negotiated if the application implementation supports it. The WebRTC media plane is designed to avoid, as far as possible, the need to relay peer-to-peer media streams to intermediaries. WebRTC media plane also incorporates an exchange of information on the quality of the network. This creates more intricate options for adapting the media coding to best-effort network conditions [5].

Once the connection between peers is established they start streaming data. In this case, KinectRTC uses the two kinds of streams that WebRTC provides; multimedia (video and audio) and the data channel. In the case of multimedia streams, WebRTC can be configured to manage these streams and adapt the quality of the RGB image and the audio to the available bandwidth. This means that if necessary the video resolution and the audio bit rate are automatically reduced to improve data transfer. On the other hand, data channels don't include yet any function to adapt transmission to the available bandwidth [47].

3.2.2.1 Server application

The server application is implemented in C++, its only purpose is coordinating peers before establishing a P2P connection. Though, WebRTC offers P2P communication, it still requires a server to keep track of the peers to open the initial connection. Peers are registered in the server, allowing the server to provide any other peer a list of available peers. After a request for connection is received and connection is established via P2P protocol, the server does not have any other role in the data interchange between the peers.

3.2.2.2 Client application

The client application was implemented in C++ using the Native C++ API of WebRTC. This implementation consisted of the PeerConnection configuration for video/audio and data transmission gathered from the Kinect. KinectRTC client was developed as a Windows application. It provides the following functionality:

- Establish the IP of the server to connect.
- Peer selection and connection/disconnection.
- Data to send selection (audio, video, depth, skeletons).

When the P2P connection is established the KinectRTC clients start streaming video, audio and data. By default Kinect drivers make Windows recognize Kinect microphones as an audio source. Then the Kinect audio source is assigned to the audio stream. When the connection is established audio is compressed and streamed in real-time.

However, Kinect is not recognized as a camera by the Windows OS. The access to the Kinect video stream was obtained via Microsoft Kinect SDK. For this purpose a customized device class was created to feed the WebRTC video stream with RGB video frames from Kinect. The video is transferred to the video stream at a rate of 30 fps, the same rate that Kinect provides it.

Moreover, WebRTC data channel can be opened to allow two different data transfer formats, text data or binary data. In this implementation a binary data channel was created and Protocol Buffers [85] were used to encode Kinect data before sending it through the data channel. The Protocol Buffers allow for fast and automatic encoding/decoding of C++ objects into binary buffers that can be sent/received over the network [66]. Depth data are also compressed using z-lib while camera parameters and skeletons are only converted to binary data.

3.2.3 KinectRTC prototypes

KinectRTC can be considered an independent development. It is an application for real-time Kinect data transmission. However it can be adapted and integrated in more complex systems to extend their communication capabilities. For the purpose of testing its features in the context of telerehabilitation, KinectRTC was integrated in Tele-MFAsT and in KiReS.

3.2.3.1 Tele-MFAsT

KinectRTC was integrated in the original Tele-MFAsT [57] framework developed in UC Berkeley for the purpose of testing the implementation. Tele-MFAsT thus facilities streaming and visualization of data (video, depth, audio and skeletal data) from remotely connected Microsoft Kinect devices. The streamed RGB and depth data are reconstructed on the receiving side and rendered inside a 3D virtual environment that allows simultaneous connection from multiple sites. The client application includes a visualization module, which displays user's real-time generated 3D avatar with overlaid movement information (i.e., skeleton), and measurement module, which performs real-time analysis of the streamed skeletal data.

The client interface is divided in sections (see Fig. 22) that correspond with the steps necessary to establish a connection between a user and a physiotherapist.

- Step1: Selection of the server which the system connects to.
- Step2: Selection of what kind of data will be sent (video, audio, depth information and skeletons). The other client will be able to show more or less information depending on this selection.
- Step3: Selection of a peer from the list and connect/disconnect controls.
- Step4: Selection of the visualization properties for the remote 3D avatar (skeleton or 3D reconstruction).

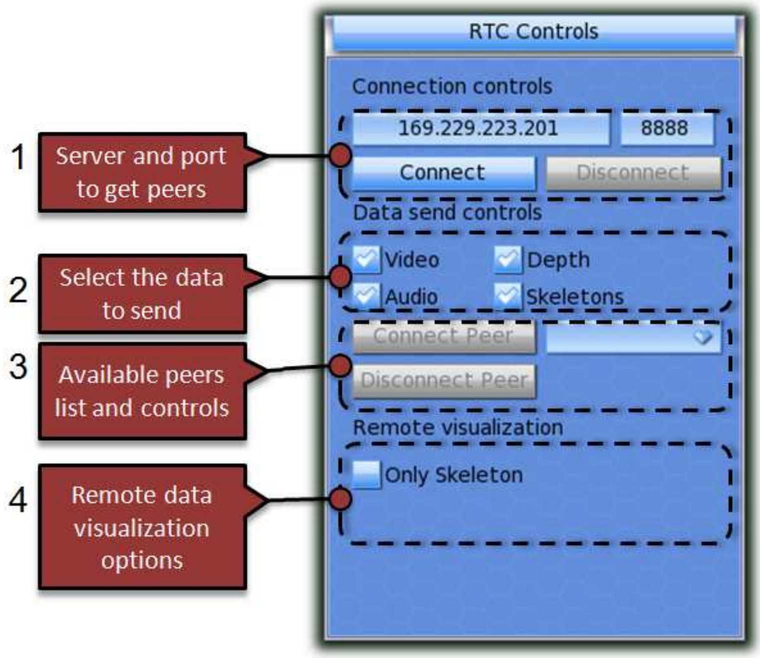


Fig. 22 - KinectRTC controls in Tele-MFAsT

The client shows a graphical interface displaying the KinectRTC control menu, remote and local video streams in the bottom and the real-time skeletons and body meshes of both users (remote user on the right and local user on the left) are rendered in a 3D environment (see Fig. 23).

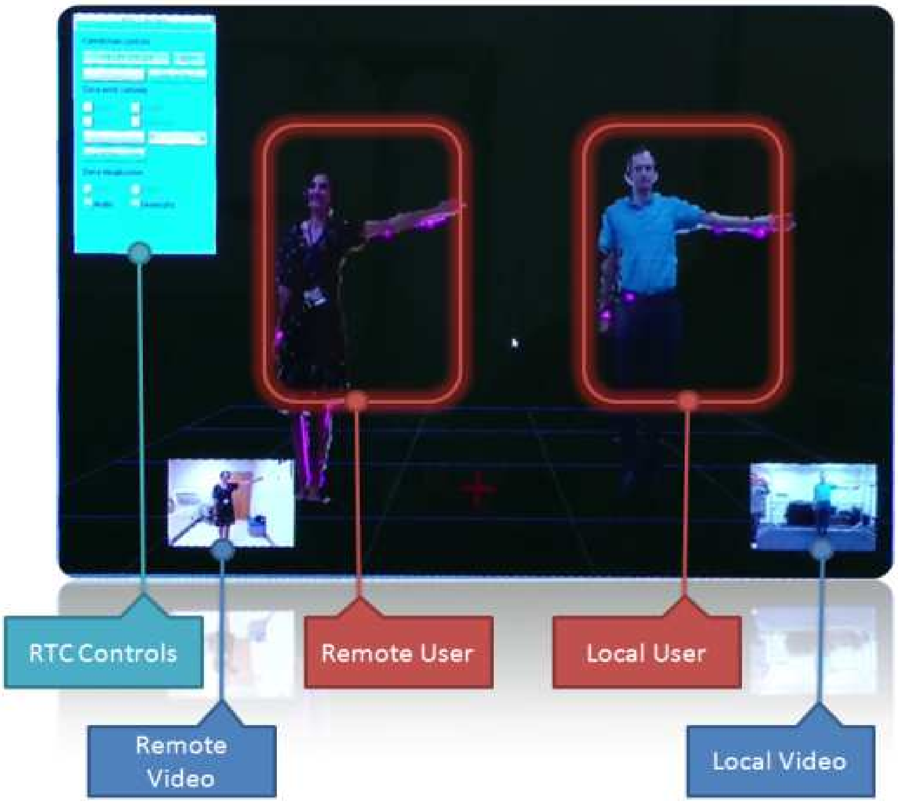


Fig. 23 - Tele-MFAsT with KinectRTC interface

3.2.3.2 KiReS

The version of KiReS with KinectRTC allows connecting the user and the physiotherapist in real time streaming video, audio and skeleton data. The interface presents a teleconference interface where local and remote video is displayed and avatars are animated with the streamed skeleton data to show real-time motion (see Fig. 24).

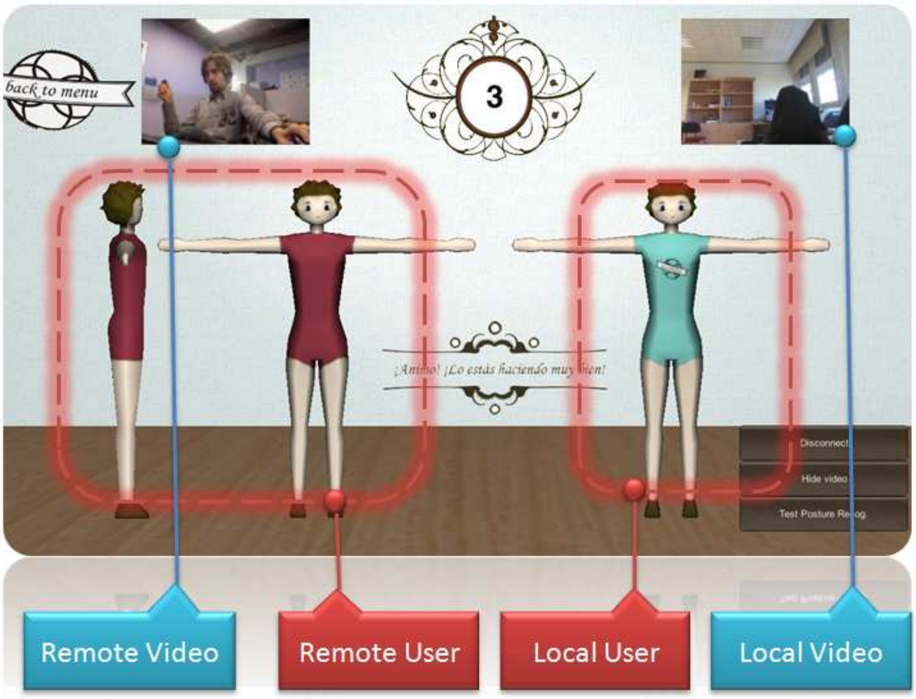


Fig. 24 - KinectRTC in KiReS

This interface allows the physiotherapist to interact with the patient by performing specific exercises directly in front of him/her. Moreover, at the same time it makes possible for the physiotherapist to observe patient's movements and correct them in real time. Turning on posture recognition features while using KinectRTC will show the patient information about how close his/her posture is to the one that the physiotherapist is performing.

3.2.4 Performance evaluation

KinectRTC was tested in both local and remote networking environments to evaluate the performance of the communication implemented via WebRTC. Several remote sessions were performed between UC Berkeley (Berkeley, CA) and UC Davis Medical Center (Sacramento, CA). Both sides used the KinectRTC client implemented on Tele-MFAsT and the server for peer listing was running at UC Berkeley side. Tests were also performed establishing a connection between the UC Berkeley, USA and the University of the Basque Country UPV/EHU, Spain. In terms of health services, this is a relatively extreme context, as the machines running the application were located at 10000Km. The tests were run 4 different days and 4 calls a day. Each day, 2 calls connecting with audio, video, skeleton data and depth images and 2 calls sending audio, video and skeleton data were established. The server was always running on the UPV/EHU side.

KinectRTC puts a special emphasis on creating stable multimedia real-time communication using Kinect as the main source of audio, video and data. As WebRTC allows sending arbitrary data, this feature fits the need of transmitting depth maps and skeleton data when working with Kinect. However, WebRTC does not manage data channels the same way it does with audio and video streams which are optimized for teleconferencing. Therefore, KinectRTC data exchange over the binary channels requires the analysis of its performance.

The metrics used in this analysis were collected on both sides of the connection. Audio and video streams data were taken from WebRTC statistics report tools and data stream statistics were taken manually through the application (as WebRTC does not implement DataChannel statistics recollection yet). The following metrics from each stream type were recorded:

Table 10 - Collected performance metrics

Audio and Video	Video	Data
Bytes sent/received	Available send/receive bandwidth	Packet timestamp
Packets sent/received/lost	Target/Actual encoding bit rate	Packet type
Current Delay (ms)	Frame height/width	Packet size
(Round-Trip delay Time) RTT	Frame rate received	Packets sent/received/lost

The tests showed that most delays occurred when receiving the depth images. Tele-MFAsT was thus unable to render the 3D avatar in synchrony with the RGB video data and the delay affected to all the binary data: camera parameters and skeletons included. Both video and audio had only minimal latencies. When depth maps were removed, the multimedia communication was much smoother in real-time. The Kinect skeletons and camera parameters, however, were still sent and, in this case, there was no noticeable delay for the real-time visualization.

Table 11 - Data size per second[8]

	Mean packet size (bytes)	Mean packets	%Total	%Total (no depth)
Audio	104.14	50.46	1.78%	2.88%
Video	960.88	124.41	40.59%	65.55%
CParam	352	30	3.59%	5.79%
Skel	1567	30	15.96%	25.78%
DepthMap	3738.4	30	38.08%	------

Table 11 shows the registered size statistics of the different types of data that KinectRTC can stream. Video and audio packets have a variable size during a connection as their quality is adapted according to the network state. The binary data packets, Camera Parameters (CParam) and skeletons (Skel), are data structures with fixed size since they always include the same number of parameters. The size of the depth maps, however, changes considerably depending on the captured scene. The size of the compressed depth map packet depends on the uniformity of the depth represented in a single frame. Large variance between the depth information in different pixels will result in larger packet size. In our scenario, we send the depth map with segmented silhouette of the user. Therefore, the size mostly depends on how close the user is to the Kinect. During a typical interaction with the system, the depth map had a stable size as the user usually stayed at the same distance from Kinect. The average depth map size during the tests was 3.65 kB with peaks from 2.47 kB to 10.53 kB.

The last two columns in Table 11 present the relative size of each type of packet with respect to the total data sent in one second with and without depth maps respectively. The results show that sending depth maps increases the required bandwidth to 38.08% of the total data transfer, which is very close to the size of the streamed video data (40.59%). The binary data packets (CParam, Skel and DepthMap) represent less than the 60% of the total transferred data when sending depth maps and around 32% when depth maps are excluded.

Table 12 summarizes the registered packet loss during the four remote tests. These results are consistent with the users experience during the tests. While video and audio streams remained stable at both locations, at the EHU side binary data delay was considerably larger during tests 1 and 3. High percentage of the skeleton and depth packages sent to EHU was lost. In the two tests, the results demonstrate that there was not only a severe delay in data transfer of depth maps, but there was

[8] Mean across all the experiments performed.

also a very high packet loss rate. In both tests with depth maps included the performance of the network was better from UPV/EHU to UC Berkeley than from UC Berkeley to UPV/EHU. Furthermore, we can observe that WebRTC kept the video and audio streams stable while binary data packets were dropped or delayed. Alternatively tests 2 and 4 without sending depth maps, show a very low rate of packets lost in audio, video and skeletons.

Table 12 - Packets lost[2]

	Video		**Audio**		**Skeleton**		**DepthMap**	
Receiver ►	BER	EHU	BER	EHU	BER	EHU	BER	EHU
Test 1	0.01%	0.11%	0.04%	47.13%	0.04%	47.13%	0.18%	57.99%
Test 2[3]	0.01%	0.00%	0.00%	5.71%	0.00%	5.71%	---	---
Test 3	0.01%	0.04%	0.14%	35.09%	0.14%	35.09%	0.14%	48.96%
Test 4[3]	0.02%	0.01%	0.00%	0.03%	0.00%	0.62%	---	---

Fig. 25 shows the target encoded bit rate and the actual encoded bit rate for the connection. In all the experiments KinectRTC detected more available bandwidth from EHU to BER, making the video bit rate higher for that connection in all the tests. The bit rate data demonstrates how the target bit rate is modified based on the state of the network. In the case of video transmission, the video frame resolution is automatically reduced to accommodate the current network bandwidth. The video stream UPV/EHU => UC Berkeley was stable at a 320x240 resolution, while the video stream UC Berkeley => UPV/EHU was reduced twice until it reached the resolution of 160x120 (Fig. 25), even when the depth maps were not included.

Fig. 26 shows how the delay measured in audio and video streams evolves during a connection. When starting the connection there is usually a peak in audio delay that lasts a few seconds, after that it drops and the delay remains relatively stable. The delay fluctuates from 60 to 130 ms for audio and from 23 to 27 ms for video, keeping the latency between audio and video within a range that guaranties the necessary QoS for real-time multimedia communication [16]. These results were common for the different tests performed, independently from the use of the data channel.

[9] Percentage of packets that did not arrive at the receiver.

[10] Tests performed without sending depth maps.

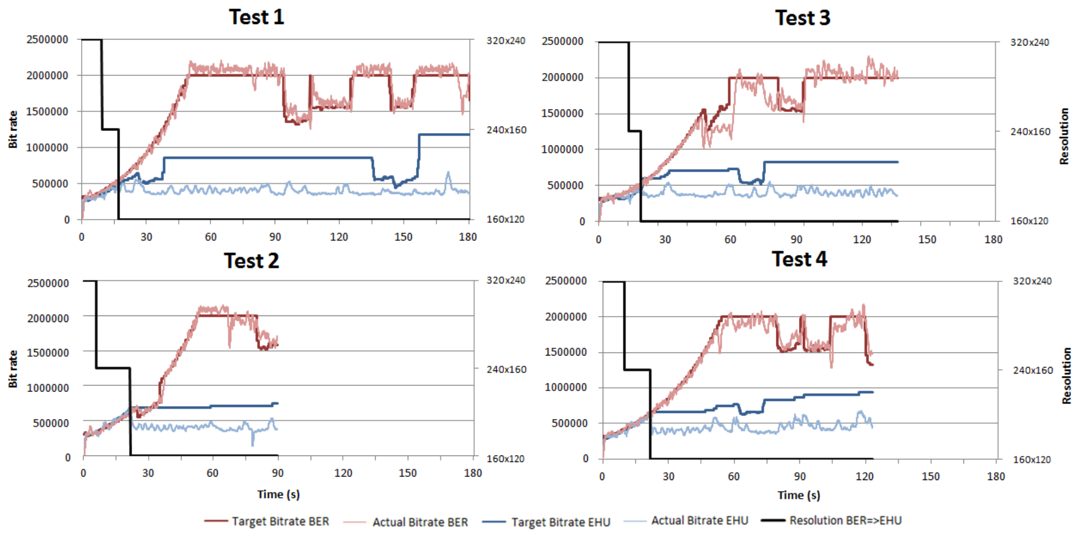


Fig. 25 - Target bit-rate vs actual bit-rate measured during tests and video resolution adaptation at Berkeley side

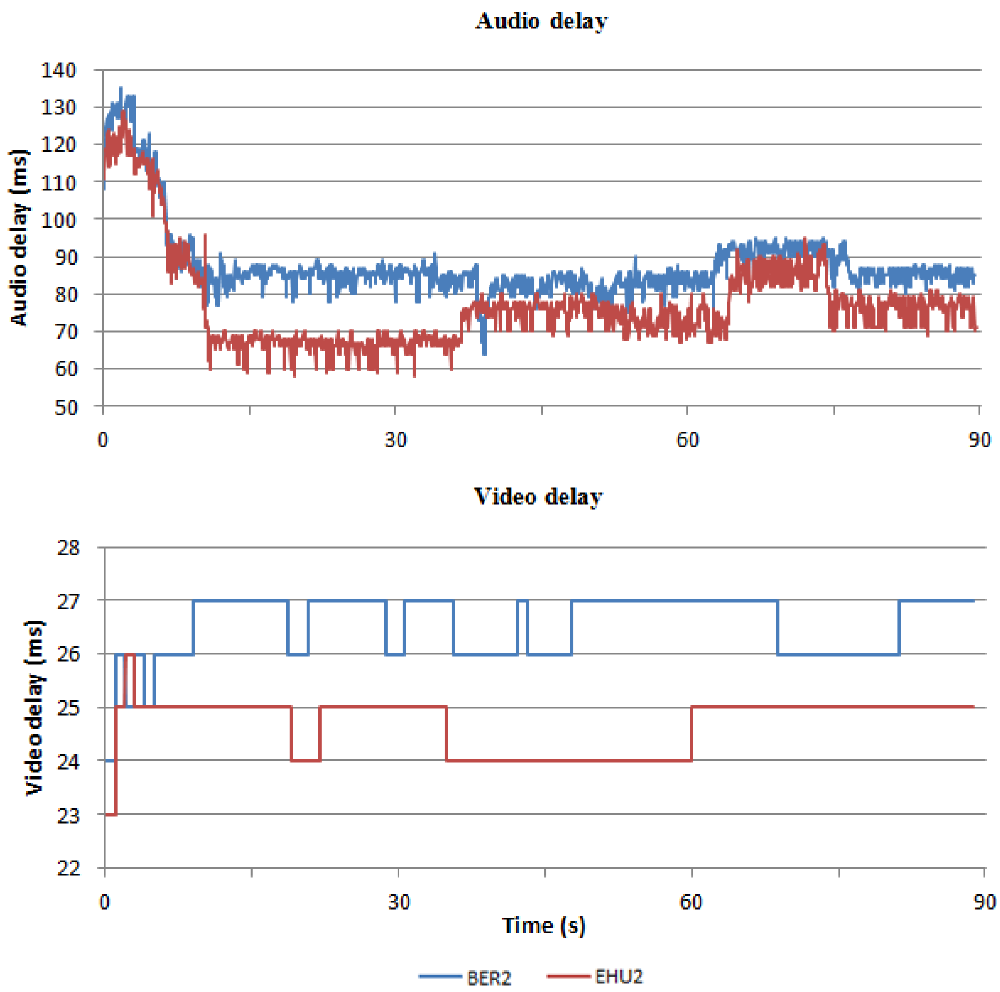


Fig. 26 - Time series of measured audio and video delay during test 2

Fig. 27 and Fig. 28 show the average audio and video delays measured at both locations during the tests. The delay was similar, independently from the type of binary data sent. It can be observed that there is no significant difference between tests 1 and 3 and tests 2 and 4. Even when the delay was present in the binary data channels, the audio and video performance was unaffected.

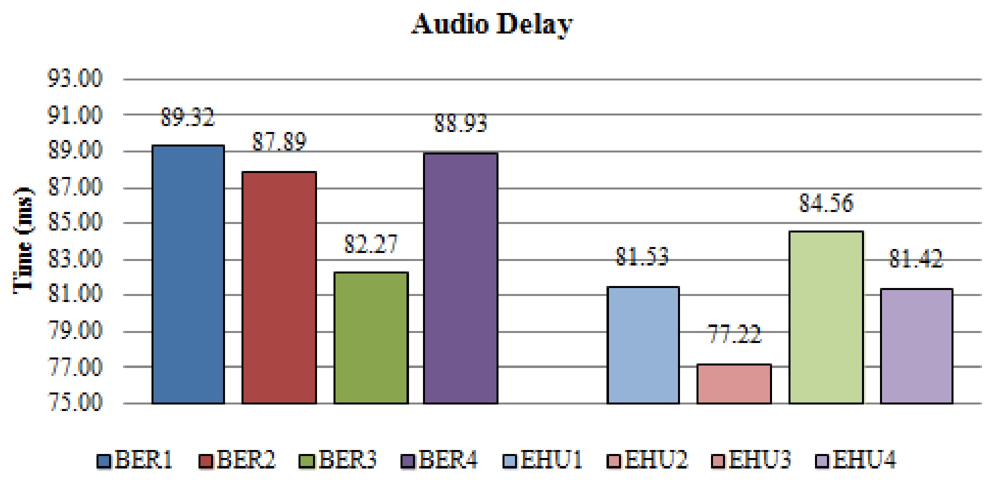


Fig. 27 - Average audio delay

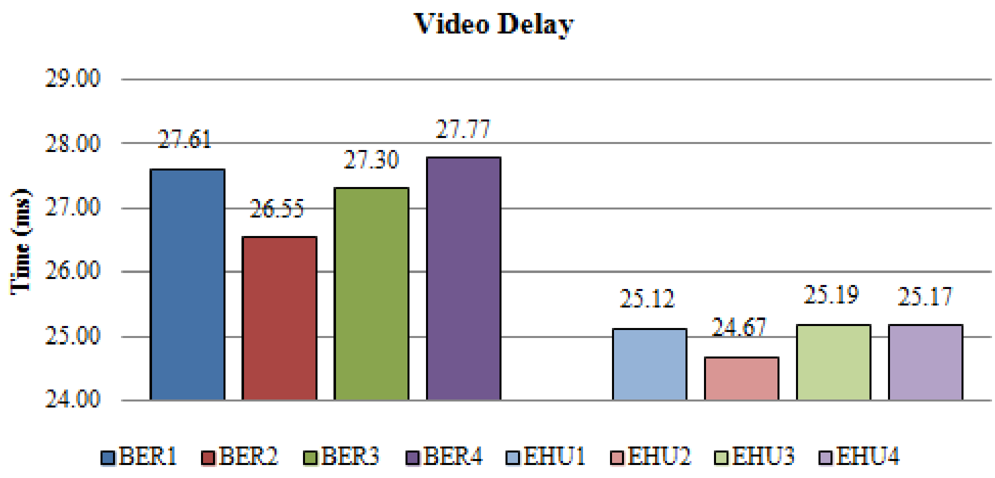


Fig. 28 - Average video delay

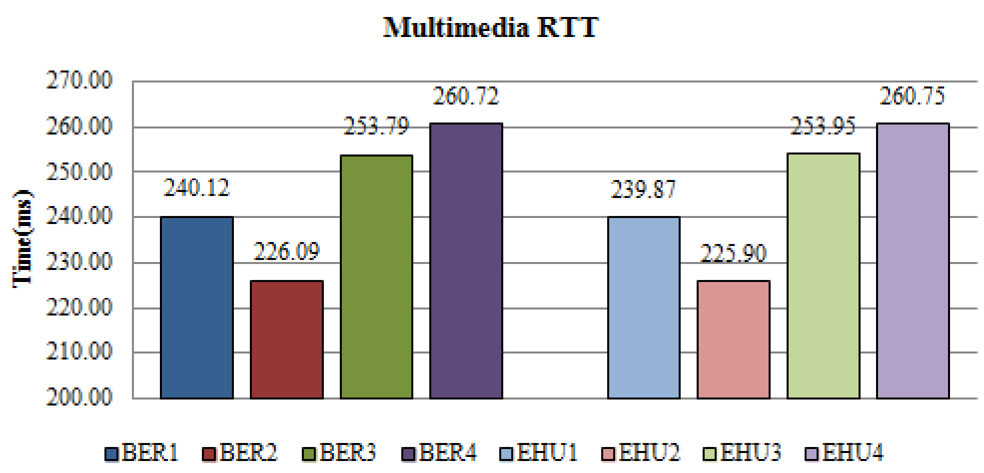


Fig. 29 - Average multimedia RTT

Finally, Fig. 29 shows the average multimedia (video+audio) RTT. The results show that the round trip delay was on average between 220ms and 260ms. The multimedia RTT results are consistent with the previous analysis, even in those cases where delay was experienced in data streaming (skeletons and depth maps) audio and video streams kept stable and fluent.

The results of the networking experiments show that KinectRTC can provide the basis for remote physical therapy with a reliable transmission of diverse medical data. Nevertheless in an unfavorable scenario, such as the network tests reported in this paper, it has been observed that binary data transmission, in particular data corresponding to depth images, generates delays and packet losses. Although interaction on such long distances is unlikely for the typical telerehabilitation, there are other applications in healthcare that may require efficient transmission of data in such scenarios (e.g., remote medical intervention in combat injuries). In the case of Kinect depth data, there is significant burden on the bandwidth as the WebRTC does not provide the level of adaptation of data transfer through the binary channels that provides for video or audio streams. The users of KinectRTC therefore have an option to choose which data are being transmitted through data channels depending on the available resources and requirements of the client application. As it is the case with KiReS, only skeletal data is required alongside the multimedia stream to provide remote interaction via 3D avatars.

3.3 Knowledge management

In this section, we present the Telerehabilitation Ontology *(TrhOnt)*, a service ontology that can assist physiotherapists in their daily tasks via reasoning supported by semantic technology. Additionally, we describe the knowledge extraction capabilities incorporated to KiReS. The novel contributions of the ontology are:

- Recording and searching information about the items that compose the physiotherapy record of a patient.
- Defining treatment protocols for a specific disorder, by selecting the exercises that must be performed in each phase of the protocol.
- Identifying in which phase of a treatment protocol a patient is at some specific moment.
- Identifying which exercises are most suitable for a patient at some specific moment, given all the information that it is known about him.

3.3.1 The telerehabilitation ontology (*TrhOnt*)

This ontology supports therapy planning by representing different kinds of knowledge (patients, protocols, exercises...) and by providing some inference services. KiReS offers an interface that provides assistance to define movements and exercises and in parallel the *TrhOnt* guarantees coherent definitions of them through knowledge descriptions.

Whenever a patient is treated in a physiotherapy unit some amount of information is generated, which includes the clinical data relevant to the current situation of the patient, as well as information regarding his personal and family history, habits, the evolutionary process, treatment and recovery. As it has been shown in other scenarios related to biomedicine [17,53,83,117], semantic technologies such as ontologies can play a relevant role in transforming that information into knowledge that facilitates the work of the physicians. In order to achieve the reasoning established for KiReS we implemented one OWL ontology following the NeOn methodology [100]. The NeOn Methodology framework presents a set of scenarios for building ontologies and ontology networks. These scenarios are decomposed into several processes or activities, and can be combined in flexible ways to achieve the expected goal (Fig. 30).

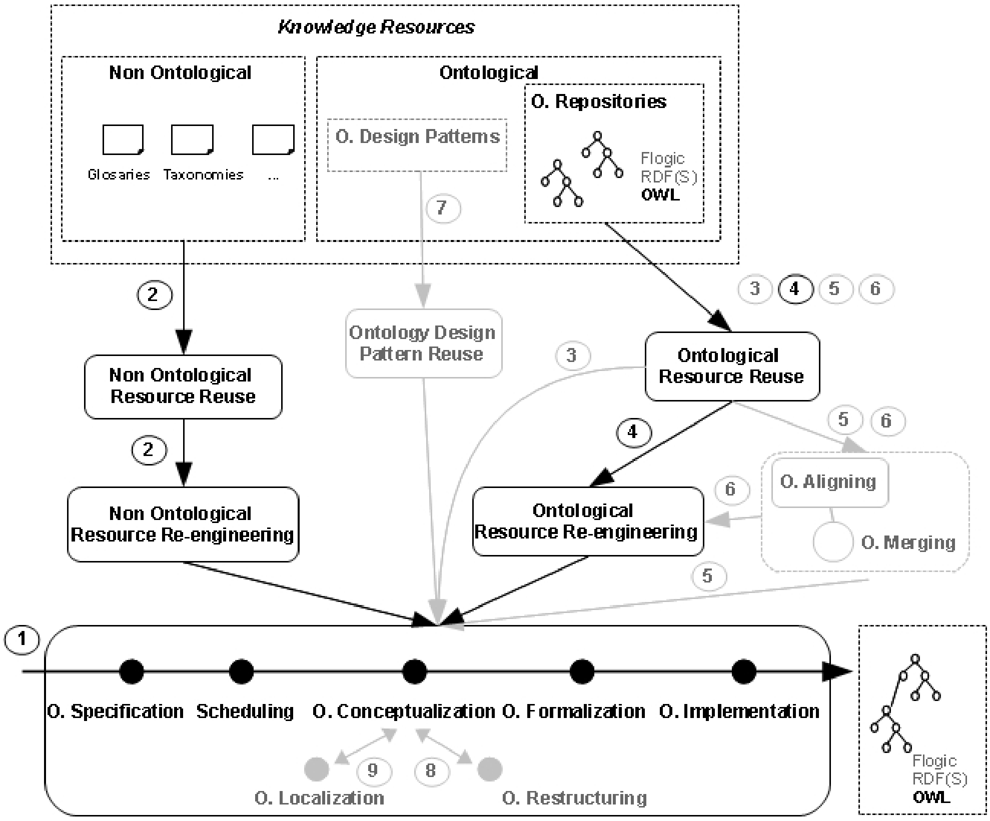


Fig. 30 - Scenarios for building ontologies, adapted from NeOn methodology

In our case three scenarios have been combined to obtain the current version of the ontology[11], which contains over 2,300 classes and properties to represent:

- The physiotherapy record of a patient.
- Movements, exercises and treatment protocols.
- A selected part of the human body. We focused on the glenohumeral joint and the body parts that are related to it.
- Other relevant information for the physiotherapeutic domain.

3.3.1.1 Planning the ontology

This scenario is composed of the five core activities to be performed in the development of any ontology: ontology requirements specification, scheduling, conceptualization, formalization and implementation.

It produces as output the Ontology Requirements Specification Document (ORSD), where information such as the purpose, the scope and the intended uses of the ontology is described. Special attention must be paid to the definition of groups of competency questions, which are the set of questions that the ontology must be able to answer. In our case, competency questions related with physiotherapy records, body parts and treatment protocols were defined, as well as some general-purpose competency questions that either fall in more that one of those categories or do not fall in any of them. The following intended uses were considered:

- Use 1: To record and search information about the items that compose the physiotherapy record of a patient.
- Use 2: To help the process of defining general treatment protocols for a specific disorder, by selecting the exercises that must be performed in each phase of the protocol.
- Use 3: To help the process of identifying in which phase of a treatment protocol a patient is at some specific moment.
- Use 4: To identify which exercises are most suitable for a patient at some specific moment given all the information that it is known about him.

The resulting ontology *(TrhOnt)* is an OWL ontology composed of four interrelated parts of knowledge (KiReS, patient and experts domain knowledge integrated in *KiReSOnt* and anatomical knowledge in *GlenoFMA)*. We have designed it as a service artifact; therefore, OWL reasoners' capabilities play a crucial role. In the following we explain more about each type of knowledge and give some examples of them.

[11]http://bdi.si.ehu.es/bdi/demos/ontology/

3.3.1.2 Anatomical knowledge (*GlenoFMA*)

The search for an ontology that covers only the glenohumeral joint and its related body parts was unsuccessful, so we expanded the search to ontologies that cover the whole human body. Two candidate ontologies were selected: OpenGALEN [86] and FMA [91]. The Foundational Model of Anatomy[12] (FMA) is a domain ontology that represents a coherent body of explicit declarative knowledge about human anatomy.

Both ontologies cover the domain of the glenohumeral joint to an appropriate extent. Since an implementation of both ontologies in OWL exists, both of them are suitable for OWL reasoners. However FMA-OWL includes unsatisfiable classes [38,78], as opposed to OpenGALEN, although the literature has proved that fully satisfiable modules can be obtained from it [71]. Both ontologies are equally considered reliable since they were developed by reputable institutions and have been used in multiple projects throughout the years [52,82,104,116]. However, we think that the hierarchy and nomenclature used in FMA are much clearer than those in OpenGALEN. Given the need of involving a physiotherapist for pruning the ontology, we opted for selecting the FMA due to its clarity, always keeping in mind that we would need to check the satisfiability of the glenohumeral joint module once extracted.

FMA-OWL in its version 4.0 contains more than 100000 classes, 156 object properties connecting the classes, and more than 700000 axioms. The scope of the FMA ontology was modified to consider just the glenohumeral joint and its related classes. We pruned the FMA ontology with the help of a module extractor [20,48] and a physiotherapist to obtain the glenohumeral joint module, *GlenoFMA*, used to represent the concepts about rehabilitation processes of shoulder pathologies. The module extractor works selecting concepts that are connected to a list of concepts passed as an argument. A concept selected this way will always be connected with some other hierarchically or by a property. In our case we performed an upper hierarchy extraction using *GlenoHumeralJoint* as the only argument for the extraction process. Then we performed a clean-up process to remove those concepts that were clearly not related with upper limbs (i.e. toe, ankle, pelvis...). After that, we applied another round of the module extractor to remove "orphan" terms that might be left. Finally, this new module was presented to a physiotherapist that checked it manually, and validated its content removing those terms he considered inadequate for the representation of upper limb pathologies in rehabilitation. This module proved to be free of unsatisfiable classes. In Fig. 31 we show a snapshot of the class *GlenohumeralJoint in GlenoFMA.*

[12] http://sig.biostr.washington.edu/projects/fm/FME/index.html

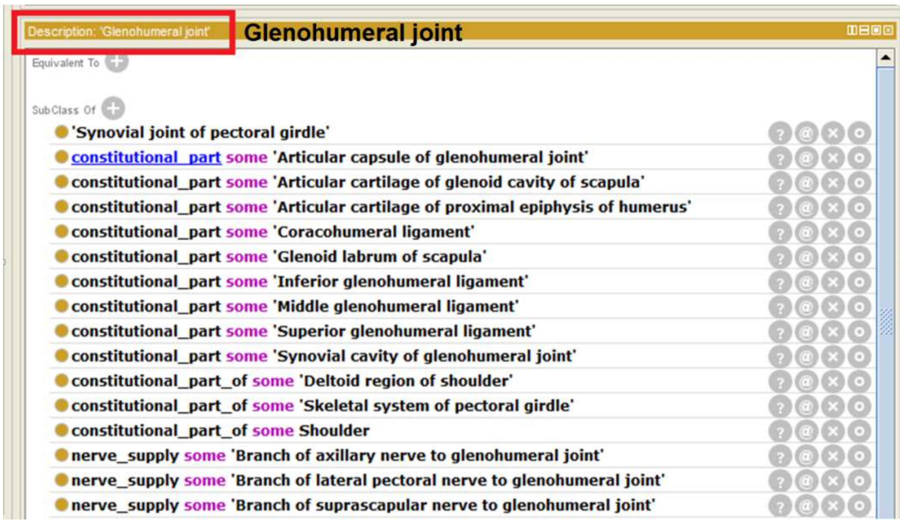


Fig. 31 - Axioms about Glenohumeral Joint in Protégé

3.3.1.3 Patient knowledge (*KiReSOnt*)

This part of the ontology is regarded as a means to record and search information about the items that compose the physiotherapy record of a patient. It consists of classes and properties for representing information such as personal and family data, goals, symptoms, results of physical examination, diagnoses, reported value in the Visual Analogue Scale (VAS) [74] and everything captured at the anamnesis.

The most important class, around which everything else was constructed, is *PhysiotherapyRecord* (Fig. 32a). Each *Patient* is related to his physiotherapy record(s), which is composed of a set of answers. A representation of its answer was defined within the physiotherapy record and includes the necessary properties (*hasVASvalue*) to store the patient's response as well as restrictions in its type and/or value (double [≥0.0,≤10.0]). When needed other classes were defined to represent more complex concepts (e.g. *MovementExploration*).

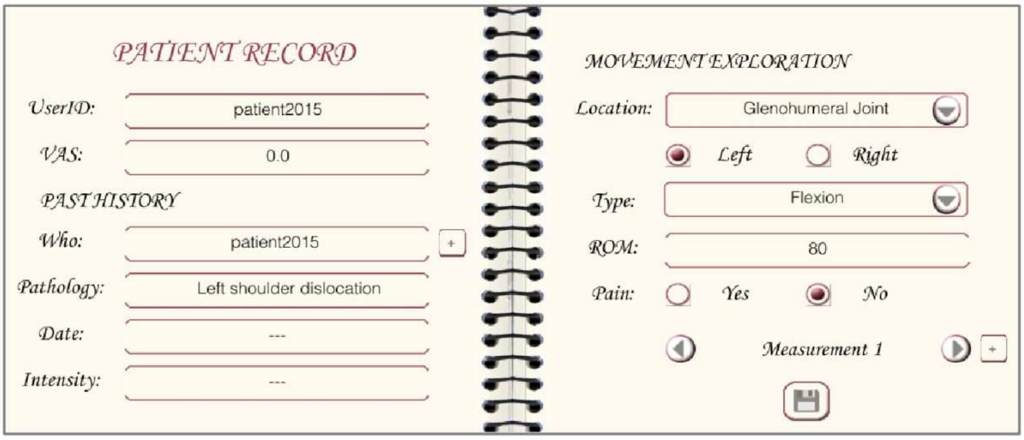
Recorded answers about a specific patient are represented as instances of classes of the ontology. Hence, the information about patient with ID *patient2015* seen in Fig. 32b is transformed, among others, into the set of triples in Fig. 32c.

By means of the *GlenoFMA* part of the ontology shoulder anatomy related concepts can be incorporated to the patients report. For example, one relevant property in *GlenoFMA* ontology is *constitutional_part*, used to describe meronymy relationships between body parts (Fig. 32d).

a)

$$
\begin{aligned}
\texttt{Patient} &\sqsubseteq \exists\texttt{hasRecord.PhysiotherapyRecord}\\
\texttt{PhysiotherapyRecord} &\sqsubseteq \exists\texttt{hasAnswer.Answer}\\
\texttt{CA1.1} &\equiv \texttt{Answer} \sqcap \exists\texttt{hasAge.integer}[\geq 0]\\
\texttt{CA1.4} &\equiv \texttt{Answer} \sqcap \exists\texttt{hasVASvalue.double}[\geq 0.0, \leq 10.0]\\
\texttt{CA1.5} &\equiv \exists\texttt{hasMovementExploration.MovementExploration}\\
\texttt{MovementExploration} &\sqsubseteq \exists\texttt{hasMovementType.MovementType} \sqcap \exists\texttt{hasLocation.Joint} \sqcap\\
&\quad \exists\texttt{hasROMvalue.double} \sqcap \exists\texttt{hasPain.boolean}\\
\texttt{MovementType} &\equiv \texttt{Flexion} \sqcup \texttt{Extension} \sqcup \texttt{ExtRotation} \sqcup \texttt{IntRotation} \sqcup \texttt{Abduction} \sqcup\\
&\quad \texttt{Adduction} \sqcup \texttt{HorizAbduction} \sqcup \texttt{HorizAdduction}\\
\texttt{CA1.7} &\equiv \exists\texttt{hasPastHistory.FamilyOrPersonalPastHistoryItem}\\
\texttt{FamilyOrPersonalPastHistoryItem} &\equiv \texttt{PathologicalCondition} \sqcap \exists\texttt{hasPatient.(Self} \sqcup \texttt{Relative)} \sqcap\\
&\quad \forall\texttt{hasIntensity.Intensity} \sqcap \forall\texttt{hasTimespan.Timespan}\\
\texttt{DislocationOfLeftGlenohumeralJoint} &\sqsubseteq \texttt{PathologicalCondition}
\end{aligned}
$$

b)



c)

⟨patient2015	rdf:type	Patient⟩
⟨patient2015	hasRecord	record2015⟩
⟨record2015	rdf:type	PhysiotherapyRecord⟩
⟨record2015	hasAnswer	ca1.4⟩
⟨ca1.4	rdf:type	CA1.4⟩
⟨ca1.4	hasVASvalue	0.0⟩
⟨record2015	hasAnswer	ca1.5⟩
⟨ca1.5	rdf:type	CA1.5⟩
⟨ca1.5	hasMovementExploration	movexp1⟩
⟨movexp1	rdf:type	MovementExploration⟩
⟨movexp1	hasMovementType	flexion⟩
⟨movexp1	hasLocation	leftGlenoJoint2015⟩
⟨leftGlenoJoint2015	rdf:type	GlenohumeralJoint⟩
⟨movexp1	hasROMvalue	80⟩
⟨movexp1	hasPain	false⟩
⟨record2015	hasAnswer	ca1.7⟩
⟨ca1.7	rdf:type	CA1.7⟩
⟨ca1.7	hasPastHistory	phi1⟩
⟨phi1	rdf:type	DislocationOfLeftGlenohumeralJoint⟩
⟨phi1	hasPatient	self⟩

d)

$$
\begin{aligned}
\texttt{GlenohumeralJoint} &\sqsubseteq \exists\texttt{constitutional\_part.`Coracohumeral ligament'}\\
\texttt{GlenohumeralJoint} &\sqsubseteq \exists\texttt{constitutional\_part.`Glenoid labrum of scapula'}
\end{aligned}
$$

Fig. 32 - Results for intended use 1.

3.3.1.4 Movements, exercises and treatment protocols (*KiReSOnt*)

The main source of knowledge to create this part of the ontology was the database used in KiReS. We used it as reference and transformed its structure into an ontology that could represent movements, exercises and protocols. Moreover, we selected the pool of movements, exercises and treatment protocols provided by expert physiotherapists since it covers a wide range of disorders with definition of phases and their conditions (Fig. 33).

Movement 2.1.5d Abduction of the Shoulder 90°		
Plane: Frontal	**Range of Motion (ROM):** 0 to 90°	
Initial posture	**Execution**	**Final posture**
		
Arms on the sides.	Move the arm upwards with the elbow in extension and the forearm in neutral pronosupination.	Arm remains separated with the elbow in extension and the forearm in neutral pronosupination.

Treatment for limited flexion of the glenohumeral joint			
Phase	**Exercises**	**Repetitions**	**Conditions**
1	...	...	...
2	211a, 211b, 211c, 211d, 212a ,212b, 213a, 213b, 214a, 214b,215a, 215b, 215c, 215d,216a	4x3	Value lower than 3.0 in the VAS scale. At least one of the following: - ROM<90° in flexion - ROM<25° in extension - ROM<90° in abduction - ROM<27° in adduction - ROM<45° in internal rotation - ROM<55 in external rotation
3	211c, 211d ,211e, 212b·, 212c, 213b, 213c, 214b, 214c, 214d, 215c, 215d, 215e, 216a, 217a, 217b, 217c, 218a, 218b, 218c, 218d, 218z	4x3	Reports no pain during the performance of exercises. At least one of the following: - 90°≤ROM<144° in flexion - 25°≤ROM<40° in extension - 90°≤ROM<144° in abduction - 27°≤ROM<36° in adduction - 45°≤ROM<72° in internal rotation - 55°≤ROM<88° in external rotation - ROM<32° in horizontal abduction - ROM<112° in horizontal adduction
...	...	...	...

Fig. 33 - Example of movement and excerpt of treatment protocol.

A re-engineering process was carried out to obtain an ontology from the gathered knowledge. The resources were analyzed to identify their underlying components. In the case of movements their name, type (flexion, extension, internal/external rotation, horizontal abduction, horizontal adduction), range of motion, plane (frontal, sagittal, transverse), initial/final posture, execution and affected body location were identified. It was also detected that in some cases a single movement is composed of more than one submovements that take place simultaneously but with different values for the {type, ROM, location} triplet. In the case of exercises their name and sequence of movements were considered. As for treatment protocols, their name, related disorder, sequence of phases (which are made up of collection of exercises), conditions of the phases, number of repetitions of each exercise and number of times the whole phase must be repeated in the same session were identified. A formal model expressed in DLs was generated from the conceptual model and later implemented in OWL using Protégé.

3.3.1.4.1 Representation of movements, exercises and treatment protocols

A *Movement* is represented by its initial and final postures, and is composed of one or more *Submovements* that take place simultaneously within that movement (An adaptation of the structure followed in Section 3.1.3). The latter is the case for movements that occur in more than one anatomical plane (e.g. diagonals) or which require the movement of two joints at the same time (e.g. both right and left glenohumeral joints). For each *Submovement* its *Joint*, *MovementType* and *ROM* are indicated. Moreover, *Mov2.1.5d* and *Mov2.2.1z* are examples of movements with one and more submovements respectively (Fig. 34).

a)

$$\begin{aligned}
\text{Movement} &\equiv \exists\text{hasComponent.Submovement}\\
\text{Submovement} &\sqsubseteq \exists\text{hasLocation.Joint} \sqcap \exists\text{hasMovementType.MovementType} \sqcap\\
&\quad \exists\text{hasROMmin.integer} \sqcap \exists\text{hasROMmax.integer}\\
\text{Mov2.1.5d} &\equiv \text{Movement} \sqcap \exists\text{hasInitialPosture.value}\{\text{'Arms on the sides'}\} \sqcap\\
&\quad \exists\text{hasFinalPosture.value}\{\text{'Arm remains separated...'}\} \sqcap\\
&\quad \exists\text{hasComponent.(Submovement} \sqcap \exists\text{hasLocation.GlenohumeralJoint} \sqcap\\
&\quad \exists\text{hasMovementType.Abduction} \sqcap \exists\text{hasROMmin.value}\{0\} \sqcap \exists\text{hasROMmax.value}\{90\})\\
\text{Mov2.1.5d} &\sqsubseteq \exists\text{hasName.value}\{\text{'Abduction of the shoulder at 90 degrees'}\}\\
\text{Mov2.2.1z} &\equiv \text{Movement} \sqcap \exists\text{hasInitialPosture.value}\{\text{'The initial posture for...'}\} \sqcap\\
&\quad \exists\text{hasFinalPosture.value}\{\text{'Arm flexed and adducted...'}\} \sqcap\\
&\quad \exists\text{hasComponent.(Submovement} \sqcap \exists\text{hasLocation.GlenohumeralJoint} \sqcap\\
&\quad \exists\text{hasMovementType.Flexion} \sqcap \exists\text{hasROMmin.value}\{0\} \sqcap \exists\text{hasROMmax.value}\{180\}) \sqcap\\
&\quad \exists\text{hasComponent.(Submovement} \sqcap \exists\text{hasLocation.GlenohumeralJoint} \sqcap\\
&\quad \exists\text{hasMovementType.Adduction} \sqcap \exists\text{hasROMmin.value}\{0\} \sqcap \exists\text{hasROMmax.value}\{50\}) \sqcap\\
&\quad \exists\text{hasComponent.(Submovement} \sqcap \exists\text{hasLocation.GlenohumeralJoint} \sqcap\\
&\quad \exists\text{hasMovementType.ExtRotation} \sqcap \exists\text{hasROMmin.value}\{0\} \sqcap \exists\text{hasROMmax.value}\{90\})\\
\text{Mov2.2.1z} &\sqsubseteq \exists\text{hasName.value}\{\text{'Diagonal of flexion, adduction and external rotation'}\}
\end{aligned}$$

Fig. 34 - Results for intended use 2 (a).

b)

$$\begin{aligned}
\text{Exercise} &\equiv \exists\text{hasInitialMovement.Movement}\\
\text{Exer2.1.5d} &\equiv \text{Exercise} \sqcap \exists\text{hasInitialMovement.(Mov2.1.5d} \sqcap \exists\text{hasNextMovement.Mov2.1.5d_inv)}\\
\text{hasNextMovement} &\sqsubseteq \text{hasFurtherMovement}
\end{aligned}$$

c)

$$\begin{aligned}
\text{TreatmentProtFlexGlenoJ} &\equiv \text{TreatmentProtocol} \sqcap \exists\text{hasInitialPhase.(Phase1FlexGlenoJ} \sqcap\\
&\quad \exists\text{hasNextPhase.(Phase2FlexGlenoJ} \sqcap \exists\text{hasNextPhase.(Phase3FlexGlenoJ} \sqcap \ldots)))\\
\text{Phase2FlexGlenoJ} &\equiv \text{Phase} \sqcap \exists\text{hasInitialExercise.(Exer2.1.1a} \sqcap \exists\text{hasNextExercise.(Exer2.1.1b} \sqcap \ldots)) \sqcap\\
&\quad \exists\text{hasSeries.value}\{4\} \sqcap \exists\text{hasConditions.Cond2FlexGlenoJ}\\
\text{Cond2FlexGlenoJ} &\equiv \exists\text{ROMFlex.double}[<90.0] \sqcap \exists\text{ROMExt.double}[<25.0] \sqcap \exists\text{ROMAbdu.double}[<90.0] \sqcap\\
&\quad \exists\text{ROMAddu.double}[<27.0] \sqcap \exists\text{ROMIntRot.double}[<45.0] \sqcap \exists\text{ROMExtRot.double}[<55.0] \sqcap\\
&\quad \exists\text{hasVASvalue.double}[<3.0]
\end{aligned}$$

d)

$$\begin{aligned}
\text{CandExe2FlexGlenoJ} &\equiv \text{Exercise} \sqcap (\\
&\quad (\exists\text{hasInitialMovement.(MovFlexGJLessEqual90} \sqcup \exists\text{hasFurtherMovement.MovFlexGJLessEqual90)}) \sqcup\\
&\quad (\exists\text{hasInitialMovement.(MovExtGJLessEqual25} \sqcup \exists\text{hasFurtherMovement.MovExtGJLessEqual25)}) \sqcup\\
&\quad (\exists\text{hasInitialMovement.(MovAbduGJLessEqual90} \sqcup \exists\text{hasFurtherMovement.MovAbduGJLessEqual90)}) \sqcup\\
&\quad (\exists\text{hasInitialMovement.(MovAdduGJLessEqual27} \sqcup \exists\text{hasFurtherMovement.MovAdduGJLessEqual27)}) \sqcup\\
&\quad (\exists\text{hasInitialMovement.(MovIntRotGJLessEqual45} \sqcup \exists\text{hasFurtherMovement.MovIntRotGJLessEqual45)}) \sqcup\\
&\quad (\exists\text{hasInitialMovement.(MovExtRotGJLessEqual55} \sqcup \exists\text{hasFurtherMovement.MovExtRotGJLessEqual55)})\\
&\quad)
\end{aligned}$$

$$\begin{aligned}
\text{MovFlexGJLessEqual90} &\equiv \text{Movement} \sqcap \exists\text{hasComponent.(Submovement} \sqcap \exists\text{hasLocation.GlenohumeralJoint} \sqcap\\
&\quad \exists\text{hasMovementType.Flexion} \sqcap \exists\text{hasROMmax.double}[\leq 90.0])
\end{aligned}$$

$$\begin{aligned}
\text{CandExe3FlexGlenoJ} &\equiv \text{Exercise} \sqcap (\\
&\quad (\exists\text{hasInitialMovement.(MovFlexGJLessEqual144} \sqcup \exists\text{hasFurtherMovement.MovFlexGJLessEqual144)}) \sqcup\\
&\quad (\exists\text{hasInitialMovement.(MovExtGJLessEqual40} \sqcup \exists\text{hasFurtherMovement.MovExtGJLessEqual40)}) \sqcup\\
&\quad (\exists\text{hasInitialMovement.(MovAbduGJLessEqual144} \sqcup \exists\text{hasFurtherMovement.MovAbduGJLessEqual144)}) \sqcup\\
&\quad (\exists\text{hasInitialMovement.(MovAdduGJLessEqual36} \sqcup \exists\text{hasFurtherMovement.MovAdduGJLessEqual36)}) \sqcup\\
&\quad (\exists\text{hasInitialMovement.(MovIntRotGJLessEqual72} \sqcup \exists\text{hasFurtherMovement.MovIntRotGJLessEqual72)}) \sqcup\\
&\quad (\exists\text{hasInitialMovement.(MovExtRotGJLessEqual88} \sqcup \exists\text{hasFurtherMovement.MovExtRotGJLessEqual88)}) \sqcup\\
&\quad (\exists\text{hasInitialMovement.(MovHorAbduGJLessEqual32} \sqcup \exists\text{hasFurtherMovement.MovHorAbduGJLessEqual32)}) \sqcup\\
&\quad (\exists\text{hasInitialMovement.(MovHorAdduGJLessEqual112} \sqcup \exists\text{hasFurtherMovement.MovHorAdduGJLessEqual112)})\\
&\quad)
\end{aligned}$$

e)

$$\text{Exer2.1.5d} \sqsubseteq \text{Exe2FlexGlenoJ}$$

Fig. 35 - Results for intended use 2 (b).

An *Exercise* is represented as a sequence of movements. Thus, every exercise must have an initial movement, which can be followed by another movement, and so on, as in the case of *Exer2.1.5d*. Moreover, some other properties were defined, such as *hasFurtherMovement*, which links a movement with any other movement further on the sequence of movements within an exercise (Fig. 35b).

A treatment protocol is represented as a sequence of phases. Among others, each phase contains a sequence of exercises to be performed during that phase, as well as the conditions that indicate when a patient is in that phase. These conditions were indicated in terms of the ROMs that patients achieve and the pain they report (pain in general and pain during the performance of the exercises). In Fig. 35c the representation of the treatment protocol for limited flexion of the glenohumeral joint is presented. It should be noticed that the set of movements, exercises and protocols in *KiReSOnt* can be extended by physiotherapists.

3.3.1.4.2 Selection of the exercises to be performed during a phase

Whenever a physiotherapist wants to create a general treatment protocol, she can rely on the ontology to select the exercises for each phase. Once the number of phases of the protocol has been defined alongside the conditions of each phase, a new set of classification rules for the selection of candidate exercises are created. Then, one ontology class is created automatically for each phase of the protocols based on the classification rules (Fig. 35d). For example, class *CandExe2FlexGlenoJ* represents the candidate exercises for phase 2 of the protocol for patients with limited flexion of the glenohumeral joint. Each of the *Mov** classes in the definition refer to the movements that the exercise must have to be classified in *CandExe2FlexGlenoJ*. More precisely, *MovFlexGJLessEqual90* represents those movements of flexion of the glenohumeral joint with a ROM lower or equal to 90°. Any exercise that contains this movement (or any of the aforementioned *Mov** movements) either as initial movement or later in the sequence is classified as *CandExe2FlexGlenoJ*, for instance *Exer2.1.5d*, and will be presented to the physiotherapist. If she selects the exercise, a new assertion is created (Fig. 35e), where *Exer2.1.5d* is no longer only candidate but also a proper exercise of phase 2 (it subsumes *Exe2FlexGlenoJ*). Classes for representing candidate exercises of other phases are defined likewise (see *CandExe3FlexGlenoJ*). Beware that one of the classes (*CandExe3FlexGlenoJ*) subsumes the other (*CandExe2FlexGlenoJ*), meaning that all the exercises classified as *CandExe2FlexGlenoJ* are also classified as *CandExe3FlexGlenoJ*, because at any point the physiotherapist should be able to select milder exercises (For example to warm the joint up).

3.3.1.4.3 Phase assignment

The ontology is used as a means to help the process of identifying in which phase of a treatment protocol a patient is at some specific moment. This is done by taking into account the results of the movement explorations of the patient at that time. As in the previous case, the classification is guided by the conditions specified in the phases of the protocols. In this case, conditions regarding the ROM and the pain are considered. Then, one ontology class is created automatically for each phase of each protocol based on the latter conditions. For example, in Fig. 36 the definition of the classes *Patient2FlexGlenoJ* and *Patient3FlexGlenoJ* can be seen, which represent those patients which are in phase 2 and 3 of the protocol to treat the limited flexion of the shoulder respectively. Each of the classes *MovExplo** in the definition refers to one type of movement exploration that the patient may have had. For instance we present the definition of *MovExploFlexGJLessThan90* to indicate an exploration of the flexion of the shoulder where the ROM achieved by the patient is below 90°. The other explorations are defined likewise. Thus, whenever a patient has a movement exploration that satisfies the definition of any of the *MovExplo** classes in

Patient2FlexGlenoJ and reports a value lower than 3.0 in the VAS, the patient will be classified as belonging to the class *Patient2FlexGlenoJ*.

```
      Patient2FlexGlenoJ ≡ Patient ⊓ ∃hasRecord.(PhysiotherapyRecord ⊓ ∃hasAnswer.(CA1.4 ⊓ ∃hasVASvalue.double[<3.0]) ⊓
                           ∃hasAnswer.(CA1.5 ⊓ ∃hasMovementExploration.(MovExploFlexGJLessThan90 ⊔ MovExploExtGJLessThan25 ⊔
                           MovExploAbduGJLessThan90 ⊔ MovExploAdduGJLessThan27 ⊔ MovExploIntRotGJLessThan45 ⊔
                           MovExploExtRotGJLessThan55)))
MovExploFlexGJLessThan90 ≡ MovementExploration ⊓ ∃hasLocation.GlenohumeralJoint ⊓ ∃hasMovementType.Flexion ⊓
                           ∃hasROMmax.double[<90.0]
      Patient3FlexGlenoJ ≡ Patient ⊓ ∃hasRecord.(PhysiotherapyRecord ⊓ ∃hasAnswer.(CA1.5 ⊓
                           ∃hasMovementExploration.((MovExploFlexGJBetween90And143 ⊔ MovExploExtGJBetween25And39 ⊔
                           MovExploAbduGJBetween90And143 ⊔ MovExploAdduGJBetween27And35 ⊔ MovExploIntRotGJBetween45And71 ⊔
                           MovExploExtRotGJBetween55And87 ⊔ MovExploHorAbduGJLessThan32 ⊔ MovExploHorAdduGJLessThan112) ⊓
                           ∃hasPain.value{false})))
```

Fig. 36 - Results for intended use 3.

For instance, if the triples in Fig. 32c are taken into account, patient *patient2015* would be classified as a *Patient2FlexGlenoJ*, because he has reported a VAS value of 0.0 (< 3.0) and there exists in his current physiotherapy record a movement exploration of flexion of the glenohumeral joint where he achieved a ROM of 80° (which satisfies conditions of the class *MovExploFlexGJLessThan90*). Beware that the classification of the patient evolves alongside his evolution in the therapy: if after being in phase 2 and performing the exercises recommended for that phase the aforementioned ROM increases to 100° and the patient reports no pain when performing those exercises, the patient would no longer be classified as a patient of phase 2, but as a patient of phase 3 (see definition for *Patient3FlexGlenoJ*).

3.3.1.5 Experts' domain knowledge (*KiReSOnt*)

TrhOnt also includes axioms that reflect specific knowledge about characteristics of recommended (and contraindicated) exercises depending on patient's state. The ontology is also regarded as a means to identify which exercises are most suitable for a patient at some specific moment given all the information that it is known about him. Three cases are considered:

1) *Recommended exercises due to classification in one phase of a protocol*: as each patient is classified in a phase of a protocol the exercises that were selected for that phase are recommended for the patient.
2) Recommended/Contraindicated exercises due to general physiotherapy knowledge: General axioms about physiotherapy have been added to the ontology to represent knowledge such as *"A patient with a personal past history of dislocation of glenohumeral joint should not perform exercises that contain abduction movements with a ROM greater than 80°"*.
3) *Recommended/contraindicated exercises for a specific patient:* The physiotherapist can specify at any time that an exercise is recommended/contraindicated for a specific patient. For example "*patient2015 should not perform exercises that contain extension movements*".

Object properties recommended and contraindicated have been created to represent these facts. Moreover, when case (3) applies, a new class is defined as the set that only contains the current patient (Fig. 37).

$$\text{Patient3FlexGlenoJ} \sqsubseteq \exists\text{recommended}.\text{Exer3FlexGlenoJ} \quad (1)$$

$$\begin{aligned}\text{PatientPastDislocationLeftGlenoJ} \equiv\ & \text{Patient} \sqcap \exists\text{hasRecord}.(\text{PhysiotherapyRecord} \sqcap \\ & \exists\text{hasAnswer}.(\text{CA1.7} \sqcap \\ & \exists\text{hasPastHistory}.(\text{DislocationOfLeftGlenoJ} \sqcap \\ & \exists\text{hasPatient}.\text{Self}))) \quad (2)\\ \text{PatientPastDislocationLeftGlenoJ} \sqsubseteq\ & \exists\text{contraindicated}.\text{ExerAbduLeftGlenoJGreaterThan80}\end{aligned}$$

$$\begin{aligned}\text{PatientPastDislocationRightGlenoJ} \equiv\ & \text{Patient} \sqcap \exists\text{hasRecord}.(\text{PhysiotherapyRecord} \sqcap \\ & \exists\text{hasAnswer}.(\text{CA1.7} \sqcap \\ & \exists\text{hasPastHistory}.(\text{DislocationOfRightGlenoJ} \sqcap \\ & \exists\text{hasPatient}.\text{Self}))) \\ \text{PatientPastDislocationRightGlenoJ} \sqsubseteq\ & \exists\text{contraindicated}.\text{ExerAbduRightGlenoJGreaterThan80}\end{aligned}$$

$$\begin{aligned}\text{Patient2015} \equiv\ & \{\text{patient2015}\} \quad (3)\\ \text{Patient2015} \sqsubseteq\ & \exists\text{contraindicated}.\text{ExerExtension}\\ \text{ExerExtension} \equiv\ & \text{Exercise} \sqcap \exists\text{hasInitialMovement}.(\text{MovExtension} \sqcup \exists\text{hasFurtherMovement}.\text{MovExtension})\\ \text{MovExtension} \equiv\ & \text{Movement} \sqcap \exists\text{hasComponent}.(\text{Submovement} \sqcap \exists\text{hasMovementType}.\text{Extension})\end{aligned}$$

Fig. 37 - Results for intended use 4.

These axioms combine classes and properties that refer to the user data (e.g. *hasDiagnosis*, *hasGoal*, *hasVASvalue*), to body parts (e.g. *GlenohumeralJoint*) and to movements and exercises (e.g. *hasROMmax*). Due to the information recorded in the Patients knowledge part, inference services (such as class subsumption and instance realization) applied on expert's domain knowledge are able to offer a list of recommended exercises for that patient.

3.3.2 Knowledge Extraction

The data obtained during exercise executions and evaluations that are stored in the database of KiReS can be analyzed on the one hand, to incorporate it to the *TrhOnt* ontology and on the other hand, to provide more information to the physiotherapists.

For example, the raw data obtained from the telerehabilitation session of a user can be used to apply a statistical analysis on it and find relevant information for the therapist. In this case, the exercise is a shoulder exercise with a symmetric movement in which both arms are moved at the same time. The user raises up both arms to the head and then moves them down. The raw data consist on the results of evaluating the trajectories of several body joints during a session (see Fig. 38). A statistical analysis allows obtaining the correlation among these data that can be of interest for the physiotherapist.

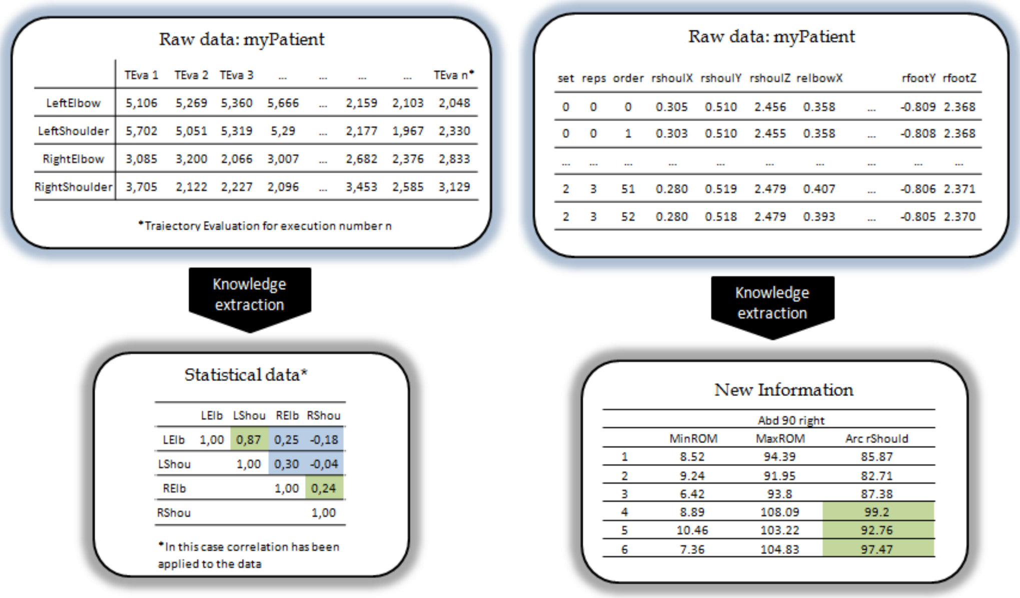


Fig. 38 - Knowledge extraction examples 1 and 2

The conclusion is that "The left arm is progressing, both elbow and shoulder are recovering, but the recovery of the right arm might not be uniform and the patient may need a check". New assertions will be added to the ontology that will be used to notify the physiotherapist.

In the second example on Fig. 38, the raw data consist of the position coordinates of the body joints recorded with Kinect on several executions of an exercise (Right shoulder abduction 90º). This data can be processed to obtain the angular values of the right shoulder and check the performance of the user. For this analysis, KiReS takes into account the maximum, minimum and arc ranges the patient is achieving during shoulder exercises. In this case, the range of movement after several executions shows that the patient is reaching higher ranges than expected (the goal of this exercise is 90º).

The conclusion is "The patient is doing better, reaching repeatedly ranges higher that 90, therefore his exercise program may need a check". In this second case, new assertions will be added to the ontology to update the patient's state (see an example below) and this new knowledge will trigger a reevaluation process.

```
<myPatient   is-a             Patient>
<myPatient   hasExecution     exe4>
<exe4        is-a             Execution>
<exe4        hasMovementType  abduction>
<exe4        hasLocation      rightGlenoJ>
<exe4        hasArcRange      99.2>
```

3.4 Trials

In this section, the trials carried on to test and validate KiReS and its features are presented. The objectives of these trials were validating the recognition algorithm designed for KiReS, validating KiReS for the provision of exercises to patients and evaluating the satisfaction of the users with the system. The major contributions made in these trials are:

- Results of testing the monitoring capability of KiReS with real patients.
- The evaluation through questionnaires of the usability and satisfaction using KiReS.
- The clinical validation of KiReS with patients with shoulder disorders and patients with Total Hip Replacement (THR) surgery.

3.4.1 Common aspects of the trials

In this section we present the results obtained from three trials that took place during the development of KiReS. Two of them were held in a rehabilitation center in Donostia-San Sebastian (Spain) with the collaboration of Matia Foundation [30] and another one took place at a rehabilitation center in Bilbao (Spain). The third trial took place at Queen Elizabeth II Jubilee Hospital in Brisbane, Australia.

Aside from the pathologies that the patients suffer, all the trials that were carried out during this work shared some common aspects that will be addressed in this section in order to avoid repeating content along this chapter.

3.4.1.1 Data analysis

Kinect raw data consists of a skeleton structure composed of 20 3D points that represent 20 body joints (Head, Shoulders, Elbows, Wrists, Hands, Spine, Hips, Knees, Ankles and Feet). During these trials KiReS stored in a local database all the data regarding the exercises the patients performed, including the results they obtained and other performance measures. All data collected in this study were analyzed descriptively. The following metrics (all of them including time stamps) were derived from the raw data captured during exercises:

- Joint position: The 3D coordinates of 20 body joints.
- Posture evaluation: A rating value that represents the similarity between postures.
- Resistance time: The actual hold time for the postures.
- Movement evaluation: The limb angles changes during a movement.
- Movement speed: angular velocity of relevant limbs.
- Exercise rating: Overall rating of the exercises.

3.4.1.2 Supervision and confidentiality

At all times we counted with the presence and assistance of a physiotherapist that helped us to assign the most adequate exercises for each of the users according to their particular movement limitations.

Those participating in the study signed an informed consent form including a privacy protection statement, which was written with the endorsement of the respective institutions.

Prior to commencing the session, we proceed presenting the system to each of the participants and we gave a brief explanation of the objectives and achievements of the project so far, the objectives of the trial and finally, a tutorial about how the system works and the elements that they were going to find in the interface during the therapy session. After that, they started doing the exercises they were assigned.

3.4.1.3 Questionnaires

In order to retrieve patient's subjective perceptions we used a Likert scale questionnaire that patients completed at the end of each exercise session. The questionnaire consisted of 13 questions about the session with five possible answers from 1 (strongly disagree) to 5 (strongly agree). The questions were divided in 3 categories: the system; the experience of the user; and the interface (see Table 13). There was a yes/no question asking whether the users had previously heard about telerehabilitation and also an open-ended question in which users could write any opinion or suggestion they had about their experience with KiReS.

Table 13 - Questionnaire

If this is your first visit, have you ever heard about telehealth or telerehabilitation?
System
1. This system could help with my rehabilitation.
2. This telehealth exercise session is as good as a usual exercise session.
3. I think this system would help me do my exercises at home.
User experience
4. I am satisfied with the telehealth exercise session.
5. I would like to use this system again.
6. It was easy using the system.
7. Getting used to exercising with the system was hard for me.
8. The telehealth system worked well.
Interface
9. I liked the way that the system looked.

10. The system helped me to perform the exercises.
11. It is useful to see my movements on the screen.
12. The instructions to perform the exercises helped me.
13. The system was confusing to use.

3.4.2 Matia Foundation

Participants were recruited from a rehabilitation centre of the Matia Foundation in Donostia-San Sebastian. The trials were made with 15 patients selected by physiotherapists of the Matia Foundation that agreed to participate in a rehabilitation session using KiReS. Patients had an average age of 66 in a range from 53 to 85. All of them suffered from shoulder disorders and had been going to rehabilitation for at least one month. In the first trial a group of 8 patients participated, the resting 7 patients participated in the second trial.

Prior to the arrival of the patients, KiReS was set-up with the movements and exercises needed for the trial. A physiotherapist recorded a set of exercises appropriate for users with shoulder disorders. She recorded 8 postures and 6 movements (these 6 movements where reversed making a total of 12 movements) and using our managing tool she combined them into 6 different exercises. The recorded movements plus the reversed version of them were the following: shoulder abduction, hands to mouth, shoulder extension, shoulder flexion, hands to head, and shoulder rotation.

The patients came one by one to test KiReS and each one took a 15-minute rehabilitation session. The results of this trial were also used to evaluate the performance of the recognition algorithm in KiReS (see Section 3.1.3.10).

3.4.3 Rehabilitation centre at Bilbao

KiReS was tested in a trial we performed in a rehabilitation center at Bilbao. A physiotherapist from the centre selected 11 patients that agreed to participate in a rehabilitation session. All users suffered from shoulder disorders in only one of their arms and had been going to rehabilitation for at least one month. The users had an average age of 45 in a range from 32 to 58.

Prior to the arrival of the patients, KiReS was set-up with the movements and exercises needed for the trial. A physiotherapist recorded a set of exercises appropriate for users with shoulder disorders based on standard therapy protocols. He recorded 27 postures and 16 movements (these 16 movements where reversed making a total of 32 movements) and using our managing tool he combined them into 11 different exercises. The recorded movements plus the reversed version of them were the following: left shoulder abduction 90º, right shoulder abduction 90º, left shoulder adduction 90º, right shoulder adduction 90º, left shoulder flexion 90º, right shoulder flexion 90º, left shoulder extension, right shoulder extension, left shoulder flexion 180º, right shoulder flexion 180º, left external rotation 90º, right external rotation 90º, left internal rotation 90º, right internal rotation 90º, left diagonal of abduction, internal rotation and extension and right diagonal of abduction, internal rotation and extension.

The users came one by one to test the system; each user took a 20-30 minute rehabilitation session.

3.4.4 Questionnaire results (Matia and Bilbao)

The first question of the test was to check whether users were aware of recent technologies applied to their pathology. We found that only two of them (one on each group) had heard about the concept of telerehabilitation. Even though our test was oriented to checking the functionality and usability of our telerehabilitation system and gathering the impressions of the users, we found it relevant that the users had knowledge neither about telerehabilitation nor the benefits that these systems can provide to them. And this also indicates that the whole concept of the system was new to them.

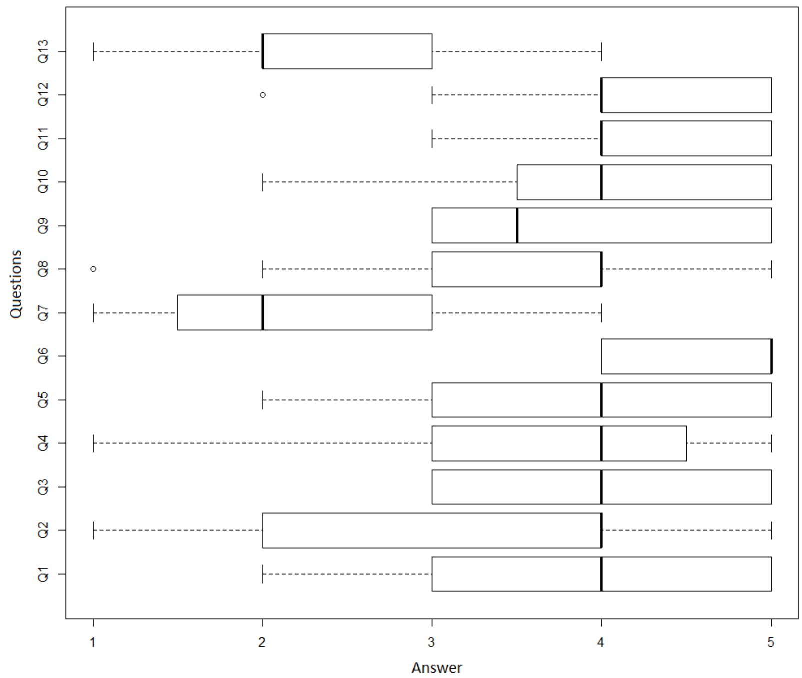


Fig. 39 - Questionnaire results Matia (median & IQR)[13]

[13] As questions 7 and 13 are negative, lower values are better

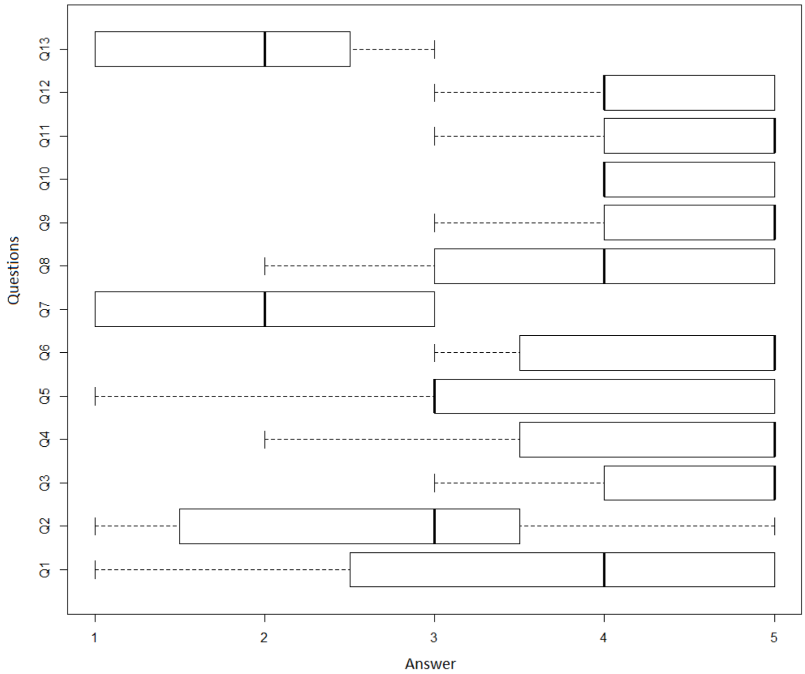


Fig. 40 - Questionnaire results Bilbao (median & IQR)[12]

This early trial results showed some aspects that we consider relevant about the users' interaction and experience with the system (see Fig. 39 and Fig. 40). First, we found that the interaction with Kinect was easy to learn for the users and they found the system comfortable to interact with. Second, they saw the system as a complement to their therapy that can improve medical attention but not as effective as the ordinary session. Third, they showed a predisposition to using the system again and felt satisfied with the experience. Finally, the overall impression of the interface content was positive (M:3.43 and A:4.45) and users found the information 3D avatars gave to them helpful. In the open-ended question some of them wrote down an answer, two of the users commented they "liked the system" and that it was "a positive experience", another one stated that "with some adjustments it will be useful" and one asked for "a bigger font in the interface". Their feedback related to the interface and the interaction with KiReS was taken into account to further improve the system.

The three categories (system, personal experience and interface) of the test showed "quite agree" and had very similar results M:3.38-A:3.77, M:3.59-A:3.59 and M:3.55-A:4.05 respectively, so globally, we can say the users were moderately satisfied with the system and showed interest in using it. There were no significant differences in the evaluations reported from both participant groups. (X^2=16.49, df=2, p <0.1871).

From the point of view of the accuracy recognizing exercises, the system recorded a total of 559 exercise executions in Matia. From these executions the system recognized 106 of them as incorrect executed exercises, even though none of the patients had used a system like KiReS before, 81.04% of the exercises performed by the patients were categorized as correct. At Bilbao we recorded 405 exercise executions with 48 of them identified as incorrect executed exercises, getting a 88.14% of correct executions.

3.4.5 Validation with total hip replacement patients

In this trial we made a full deployment of KiReS to test it in several rehabilitation sessions with a group of patients that had Total Hip Replacement (THR). It is a common surgery in many countries. For example, the Agency of Healthcare Research and Quality (USA) reports more than 285,000 THRs are performed each year in the United States and this number is forecast to double in the next twenty years [58].

Following this surgery, rehabilitation is a critical component for resuming normal activities of daily living. Maire et al. [67] indicate that the improvement in physical fitness and functional status as a result of rehabilitation is associated with better health status after hip replacement. Research, such as that conducted by Wang et al. [109], show that preoperative customized exercise programs are effective in improving the rate of recovery in the first 6 months after total hip arthroplasty. Furthermore, Unlu et al. [103] suggest that both home and supervised exercise programs are effective one year after total hip arthroplasty.

This trial had the twofold objective of validating the KiReS system for the provision of exercises for patients who have had a total hip replacement and also evaluating the satisfaction of the users with the system.

3.4.5.1 Participants

Participants were recruited from the Queen Elizabeth II Jubilee Hospital in Brisbane, Australia during February-March 2014. The inclusion criteria for the selection of the participants were: having undergone primary THR in last 4 months, full weight-bearing or weight-bearing as tolerated, and normal mentation. The exclusion criteria were: revision THR, restricted weight-bearing post-operatively and having co-morbidities preventing participation in rehabilitation program.

Patients had an average age of 56 (range 33 to 67 years), most of them (5 of 7) had hip replacement surgery in their left hip (Table 14).

Table 14 - Patients' characteristics

Age	Gender	Side	Nº Sessions	Days post-op FS[14]	Days post-op LS[15]
67	W	Right	4	28	45
61	M	Left	4	108	124
33	W	Right	1	59	59
67	M	Left	4	3	24
65	M	Left	3	7	20
45	W	Left	2	10	18
56	M	Left	1	2	2

3.4.5.2 Procedure

Patients were invited by their treating physiotherapist to participate in the study. Initially 4 sessions per patient were planned, each session of 30-45 minute duration. Ethical clearance to conduct this study was provided by the relevant institutional review board and all participants provide written informed consent prior to enrollment in the trial.

A physiotherapist at QEII Hospital performed and recorded a total of 10 exercises for both the left and the right hip using the KiReS system (Table 15). The physiotherapist also added a textual explanation for each exercise to be displayed on the interface during rehabilitation sessions.

Table 15 - Recorded exercises

	Exercise	Explanation
Hip therapy	Hip abduction	Lift your leg to the side
	Hip flexion	Lift your knee up in front of you
	Hip extension	Lift your leg behind you
	Squat	Slightly bend your knees
	Balancing	Shift your weight from side to side.

Patients received 15 minutes of education prior to commencing their first session outlining the objectives of the trial and also an explanation how the system works. Patients were also reminded that at any moment they could stop if they felt pain or were too tired to continue. Participants performed exercises in front of Kinect at a distance of approximately 2.5 meters. A chair was provided on the side of their

[14] FS: First Session

[15] LS: Last Session

surgery to hold and lean on during the exercises if necessary. The tutorial included performing 2-3 repetitions of an exercise to familiarize them with the system prior to commencing their first session.

The exercise parameters for each patient such as the number of sets and repetitions for each exercise, was entered into the KiReS system by the treating physiotherapists. As sessions progressed these parameters were adjusted according to the clinical judgment of the physiotherapist, increasing or reducing the number of sets and repetitions when necessary.

3.4.5.3 Results and questionnaires

During the trial, seven patients participated in a total of 19 sessions (Table 16). In these trials the system recorded a total of 3865 exercise executions (first column). From these exercises the system recognized 314 of them as incorrect executed exercises (second column), in proportional terms, most of errors centered around users 1 and 6 (Table 16 left). The KiReS system categorized 91.88% of the exercises performed by the patients as being correct. In Table 16 (right) we present the correct performed exercises classified by exercise type.

Table 16 - Correct executions by patient (left) and by exercise (right)

	Total	**Incorrect**	**% Correct**
User 1	1320	184	86.06%
User 2	1285	48	96.26%
User 3	300	17	94.33%
User 4	288	12	95.83%
User 5	487	17	96.51%
User 6	141	35	75.18%
User 7	44	1	97.73%
	3865	314	91.88%

Exercise	**Total**	**Incorrect**	**% Correct**
Hip abduction right	260	14	94.62%
Hip flexion right	240	12	95.00%
Hip extension right	340	10	97.06%
Squat right	340	127	62.65%
Balancing right	440	38	91.36%
Hip abduction left	515	30	94.17%
Hip flexion left	339	21	93.81%
Hip extension left	451	20	95.57%
Squat left	441	33	92.52%
Balancing left	499	9	98.20%
	3865	314	91.88%

Generally, there was an improvement in the accuracy of the exercises performed by participants over the course of the trial, those patients assisting to three or more sessions got significant better results (X^2=317.56, df=2, p <0.0001). Fig. 41 shows the exercise rating given by KiReS to all participants that completed at least 3 sessions (participants 1, 2, 4 and 5).

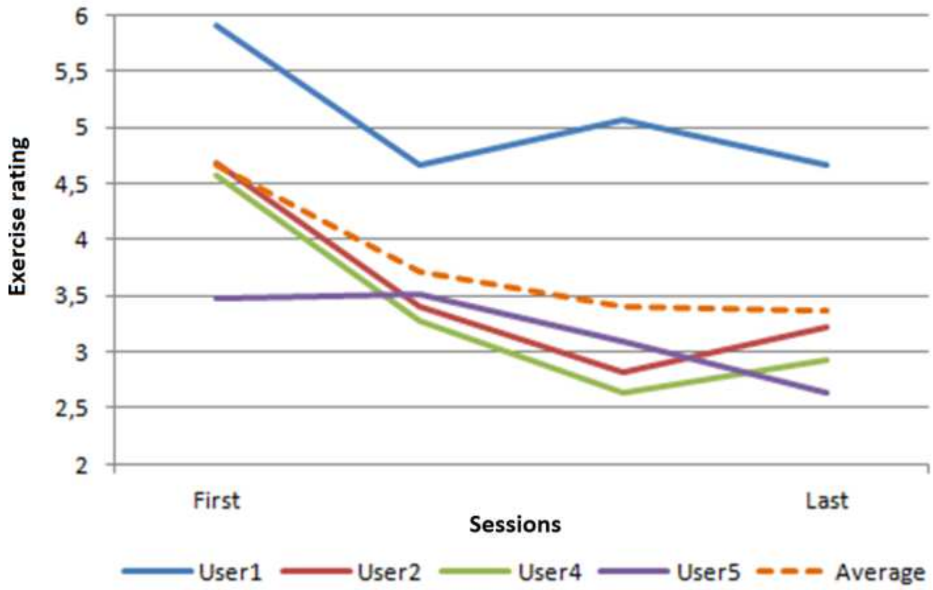


Fig. 41 - Performance over time (exercise rating - lower values are better).

Fig. 43 presents results from user questionnaires. In total 19 questionnaires were retrieved from participants. None of the users reported that they had heard about telerehabilitation or telemedicine before. Participants reported that the main negative features of the system were the size of the font and the structure of the interface, which some of them found distracting as they considered that some of the elements were not useful.

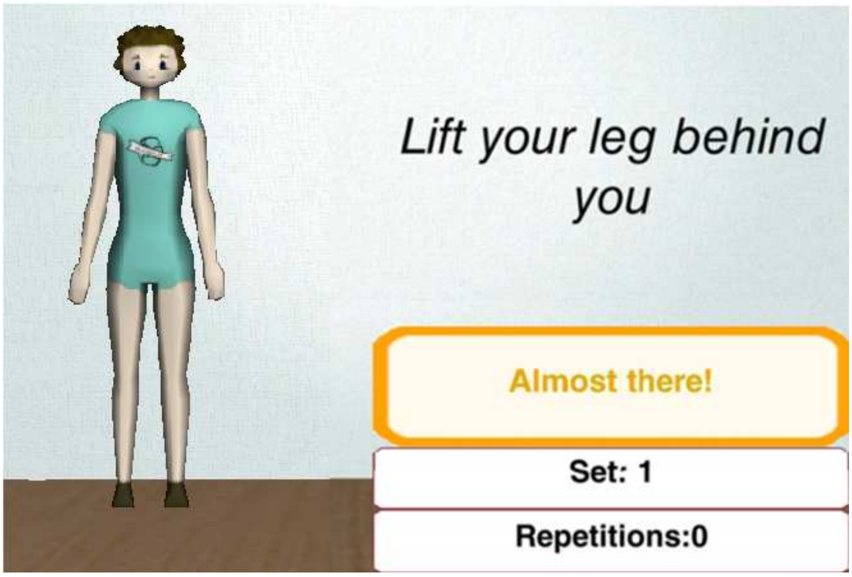


Fig. 42 - Alternative user interface

According to the feedback from the first 4 participants, an alternative user interface was designed during the trial (see Fig. 42). This interface featured simplified elements with larger fonts. The red avatar that showed the exercises was removed so the text description of the exercise becomes the main source of guidance along with the *semaphore* box. Also the size of all the elements was increased to make them more visible.

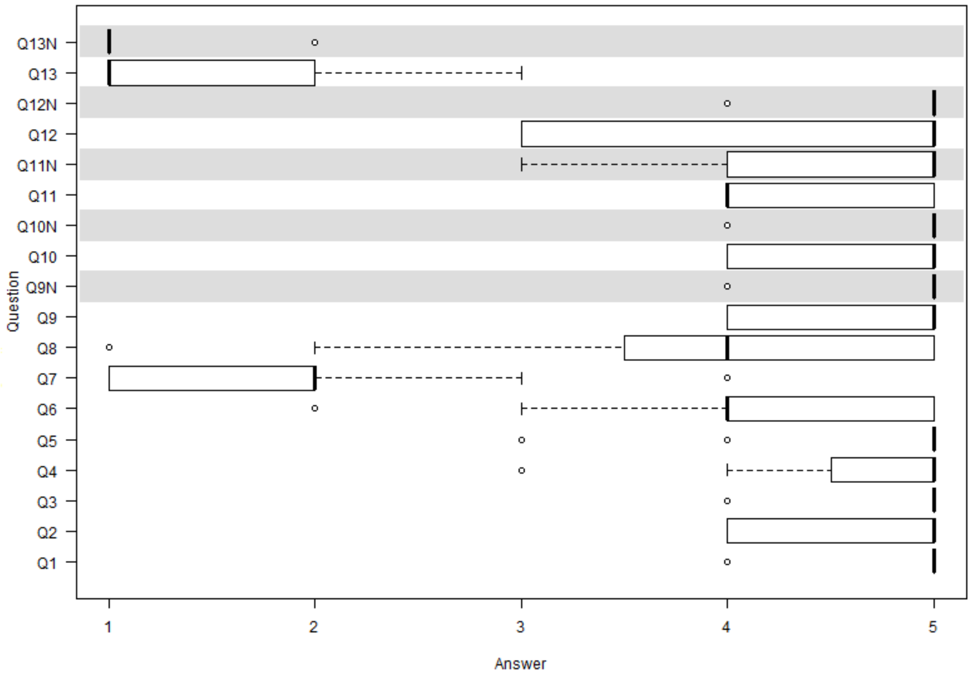


Fig. 43 - Questionnaire results (median & IQR)[16]

As the interface was adapted during the trial the questionnaire results regarding the interface are split (see Fig. 43), 13 questionnaires correspond to the original interface (white) and 6 questionnaires to the new interface (gray). The users were participative and five of them answered the open-ended question to propose ideas for improving the user experience.

3.4.5.4 Considerations about the results

We made a full deployment of KiReS defining step by step all the elements of a therapy in KiReS: postures, movements, exercises and the therapy itself. As previous studies have shown [81,101,113] patients tend to show a general support for telerehabilitation and the possibilities for physiotherapy that systems like KiReS bring. Participants also found the interaction with Kinect easy and enjoyable showing a predisposition to using the system again.

The analysis of the data collected during the sessions showed a high rate of correct executions (91.88%) even though none of the patient had used a system like this in the past. For those patients that completed at least 3 sessions, KiReS registered an increase in users' performance during the trials (X^2=317.56, df=2, p <0.0001).

[16] As questions 7 and 13 are negative, lower values are better.

The exercise performance results are quite uniform among patients but the results of User 1 and User 6 need to be highlighted (Table 16) as they showed a significantly lower rate. User 1 was the first user to test the system and we found that the system did not recognize "Squat right" exercise well (Table 16). This exercise was poorly recorded; the postures for the start and end of the exercise were found to be too similar, leading to inaccurate recognition of the exercise. The exercise was fully re-recorded to solve the problem.

Anecdotally, we observed some limitation of Kinect recognizing people of different shapes and with different clothing. User 6 was an obese user and it was noted that in two of the sessions with this user, the posture recognition was inaccurate. This low performance was due to Kinect recognition errors and not to actual wrong executions on the part of the patient.

A limitation of KiReS is that recognition is not accurate if an element that was not during the recording is introduced in the image. Nevertheless, when the exercises or the patients require an extra element (e.g. a chair for support), it can be included as long as this element was also present during the recording phase. We would therefore recommend that a set of guidelines covering these factors be developed prior to wider scale uptake of Kinect technology. Moreover, this trial highlighted that Kinect performs better in an uncluttered environment. This has implications for the deployment of the technology into the patient's home where space and furnishing is dictated.

With respect to the post-session questionnaires we had positive feedback from the patients regarding the system, although some constructive criticism, especially about the interface, was received. The levels of acceptance and usability we found were consistent with those obtained in previous research about virtual therapy and telerehabilitation [27,72,113]. The overall satisfaction with the experience of using KiReS was positive (Q4: 4.67). The participants in the trial were all familiar with doing their exercises at home and could appreciate the advantages of KiReS for facilitating their exercise routine. Patients also considered exercising with KiReS as good as regular sessions and reported that it a helpful tool for doing their exercises at home (Q3: 4.75 and Q2: 4.63). The results also reveal a high level of interest (Q5: 4.86) in the participants ongoing use of the system. Previous trials have shown this motivation on keep using similar systems for physical rehabilitation [14,80]. When the satisfaction results are considered according to the three themes (system, personal experience and interface) a mean score of 4.71 for the system and 4.4 for the personal experience category was seen. We found that the evaluation of those patients who tested the system with the new interface was higher (4.77) than with the original interface (4.43), and significantly different (X^2=6.6347, df =2, p= 0.03625). This is an expected result as we followed a user-centered interface design paradigm [115] and improvements in the new interface were based in the opinions of these very patients.

Any sufficiently advanced technology is indistinguishable from magic.

Arthur C. Clarke

CHAPTER 4 CONCLUSIONS AND FUTURE WORK

This chapter recapitulates the results of this thesis. First, the conclusions this work led to are presented. Then, the main contributions are numerated, and finally, some future research lines related to this dissertation are indicated.

4.1 Conclusions

The work presented in this dissertation has been devoted to the development of a telerehabilitation system that could overcome the limitations we identified in the existing proposals. From the beginning this development required an interdisciplinary collaboration with physiotherapists leading to the obtained results. Kinect Rehabilitation System (KiReS) is oriented to making use of the innovative interaction capabilities that Kinect offers in order to provide new functionalities for both physiotherapists and users. This dissertation covers the design, development and testing of KiReS and it features.

From the point of view of users, KiReS provides home-based telerehabilitation with a natural form of interaction. The interface includes two avatars, one with which the user can see the exercise s/he must perform and another one with which s/he can see how s/he is actually doing it. The system includes an auto-test tool which allows the user to transmit subjective information about the evolution of the therapy to the physiotherapist. From the point of view of physiotherapists, KiReS allows them to define customized therapies for the users, create new exercises just by performing them in front of the system and manage evaluation tests. Moreover, physiotherapists can also analyze the data recorded from the users in order to track the users' evolution, obtain new knowledge about exercise performance or use the data to identify and correct undesired situations.

Another relevant aspect to highlight is that KiReS is not designed for a specific pathology; the system can be loaded with a broad spectrum of exercises as opposed to the majority of proposals that consider fixed exercises to specific physical pathologies. Additionally, given the great amount of captured data from the therapy sessions (exercise executions, therapy evaluations and results of the tests) the system can carry out an intelligent integration of these data and provide smart data, which can be actionable information for the physiotherapists and the users. Finally, the ontology (*TrhOnt*) is relevant from the perspective of its usage and the information that it provides for the physiotherapists via a reasoning process. This information includes exercise recommendations for protocol design, the current phase of a protocol in which a patient is and recommended/contraindicated exercises depending of patient's current state. That is, information that can improve rehabilitation processes.

4.2 Main contributions

The main contributions of this research work are described in this section. They have been presented in the previous chapters and in the conference and journal publication resulting from these works that can be found in chapter 0. All of them share the purpose of extending and improving the features of KiReS.

4.2.1 KiReS: Kinect Rehabilitation System

The main contribution of this thesis is KiReS: Kinect Rehabilitation System, a telerehabilitation platform for physiotherapists and patients that manages therapies, records exercise sessions and analyses data to provide actionable information for physiotherapists and patients. From the point of view of patients, KiReS offers a friendly and immersive exercise interface that shows in two 3D avatars how an exercise must be executed and how the user is executing it respectively. Moreover, during a therapy session, informative elements show up-to-date information to guide and encourage the user. From the point of view of the physiotherapists, KiReS provides a library of exercises that can be used to define customizable telerehabilitation therapies. This task can be done by combining different exercises into a therapy and organizing them in progressive phases. In addition KiReS provides the feature of defining new ones by just recording them in front of Kinect. It was validated with physiotherapists and patients suffering different pathologies and we showed the viability of using Kinect for telerehabilitation. The rest of the main contributions are elements that are parts of KiReS which could be applied to other contexts or that can be considered of utility individually.

4.2.2 Kinect-based exercise recognition algorithm

We have presented a recognition algorithm that uses the data provided by Kinect. A data structure to represent movements and exercises was designed that works as the input for a recognition algorithm, which distinguishes the beginning and the end of a movement and rates its performance. We have shown the features of the descriptor defined to encode 3D postures and a similarity measure to compare descriptors. Calculating the distance between two descriptors, we establish if a captured posture is similar to another, and so decide if it can be recognized as an existing one. We have also defined how to characterize a movement and an exercise in a structure that lets us link many basic movements in complex exercises. The motion analysis algorithm based on DTW compares the user's movements in the most relevant limbs for a given exercise and rates the overall execution.

Part of the development of this algorithm consisted on its evaluation. This leaded to the creation of a series of annotated datasets containing body postures and movement trajectories from several shoulder and cervical rehabilitation oriented protocols. Experiments with volunteers and real patients showed good results in terms of accuracy recognizing their movements and efficiency in real-time.

4.2.3 KinectRTC

KinectRTC facilitates stable and secure transmission of video, audio and Kinect data (i.e., camera parameters, skeleton data, and depth image) in real-time between two peers. The remote peers can communicate to each other using 3D video and audio while the motion data captured by the Kinect are streamed for real-time feedback or stored for later analysis. This complementary functionality to video-conferencing systems was envisioned to allow for remote real-time interactive rehabilitation sessions. In KinectRTC video and audio streams are managed based on the state of the network and the available bandwidth so their quality is adapted to guarantee the real-time performance of the communication. Kinect RTC has been integrated with KiReS and Tele-MFAsT, two telerehabilitation platforms, and the results of the networking experiments showed that it can provide the basis for remote physical therapy with a reliable transmission of diverse medical data.

4.2.4 TrhOnt

The aim of *TrhOnt* ontology is to provide a reference model for the representation of the physiotherapy-related information that is needed for the whole physiotherapy treatment of a patient, since he steps for the first time into the physiotherapist’s office, until he is discharged. It allows the representation of patient's report, therapy exercises, movements and evidence-based rehabilitation knowledge; and favors reasoning capabilities over therapy data for the selection of exercises and the notification of events to the therapist.

4.3 Future work

This thesis has been devoted to the development of a telerehabilitation system. Probably, the most evident step forward in any development that has been related with Kinect in the last years is its adaptation to Kinect 2. This new Kinect will provide greater accuracy, higher resolution and more detailed skeleton and joint information. Beyond the time needed for the update of the interface of KiReS, an upgrade of the exercise recognition algorithm and its validation is the most direct course of action to improve KiReS. The new features such as extra joints and joint rotations would serve to extend the kind of exercises to recognize and the evaluation parameters to measure. Other aspects about data representation and report generation for the physiotherapist based on the data recorded have not been deepened in this work.

Beyond the improvement of body tracking that can be achieved by upgrading KiReS with Kinect 2, future extensions could include improvement in the other aspects of the telerehabilitation system we have presented. *TrhOnt* can be extended by physiotherapists, however updating manually its content (sets of movements, exercises and protocols) is a task that may require some expert knowledge about ontologies. Currently we are developing a graphical tool for this purpose which will provide an interface to define graphically the elements that compose a physiotherapy protocol step by step, simplifying the process of managing the content of the ontology.

One open problem which affects Kinect is the efficient transmission of depth images through the network. Our proposal for real-time communication with Kinect does not solve the problem of depth data compression and the management of data transmission in a context where network performance is variable. Being this is an issue for real-time communications it also opens up new possibilities to investigate how potential network delays affect the interaction and the movement feedback during therapy sessions.

Finally, another line that we have considered is enhancing the information KiReS retrieves by adding biosignal tracking devices such as pulse oximeters that measure heart rate and oxygen saturation of blood. Thus, it would be possible to extend the reasoning capabilities of the system with new inputs that could serve as trigger for new processes, such as alarms for the physiotherapist or dynamic exercise planning depending on patient's readings. Incorporating these devices to KiReS would also require the upgrade of *TrhOnt*.

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PUBLICATIONS

A. KiReS: A Kinect-based telerehabilitation system

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KiReS: A Kinect-based telerehabilitation system

David Antón[1], Alfredo Goñi[2], Arantza Illarramendi[3], Juan José Torres-Unda[4], and Jesús Seco[5]
[1,2,3]Department of Languages and Information Systems, University of the Basque Country UPV/EHU; Donostia-San Sebastián, Spain
[4]Department of Physiology, University of the Basque Country UPV/EHU; Leioa, Spain
[5]Institute of Biomedicine (IBIOMED), University of León; León, Spain
{[1]danton004; [2]alfredo; [3]a.illarramendi; [4]juanjose.torres}@ehu.es
[5]jesus.seco@unileon.es

***Abstract*—The goal of this paper is to show the main features of KiReS, a telerehabilitation system based on Kinect for Windows, that offers, for both, users and physiotherapists some specific elements that make it more friendly to them. From the point of view of users, they can see in two 3D avatars how an exercise must be executed and how they execute it respectively. This feature can help them improve exercises performance. Moreover during the rehabilitation session they will always see an informative list that shows the exercises to be done in the session. From the point of view of physiotherapists the system allows them on the one hand, to define customized rehabilitation therapies. That can be done by defining different exercises that combine pre-defined movements. Moreover, they can add tests oriented to specific illnesses so that users themselves evaluate their physical state. On the other hand, they can create new exercises just performing those exercises in front of the system and recording them. Those features, not fully supported by already existing telerehabilitation systems, provide an added value that is well valued by both groups. Moreover, a prototype of KiReS is in operation, and allowed us to test its suitability from the point of view of real time performance as well as from the point of view of usability.**

Keywords*—*Kinect, Telemedicine, Telerehabilitation, Virtual therapy.

I. INTRODUCTION

The aging population and the people higher survival to diseases and traumas that leave physical sequels are challenging aspects in the context of an efficient health management. In this scenario telerehabilitation systems that support remote physiotherapy sessions can help save healthcare costs while improving also the quality of life of people. Telerehabilitation should not be seen as a technology itself, but as the use of new technologies to improve and optimize both, rehabilitation services and users outcomes. Several studies have shown that virtual interaction can be as effective as traditional treatments, and even more, the use of systems with motion capture can increase the intensity of rehabilitation and the fun of the user [1, 2].

Nevertheless we can see that the type of virtual interaction that users have is not equal in all cases. So, we can find systems that make use of wearable devices [3-5]. Other proposals advocate that users do not wear devices but they only use them [6, 7]. Finally, with the aim of facilitating even more the interaction of users appears another trend that advocates the use of Kinect, a motion capture device that tracks user movements without any physical contact. Among the proposals that follow that trend we can distinguish those that use Kinect Xbox version [8-10] and those that use Kinect for Windows, a version that was launched in February 2012. In this last case, the proposals that can be found are mainly commercial products such as [11-13] which do not show many technical details concerning their internal behavior and are oriented to specific pathologies.

In this paper we present KiReS (Kinect Rehabilitation System), a system with which we advocate for a video tracking solution without markers that allows users to control and interact with the system through an interface that can recognize movements, voice commands and objects. We believe that non-invasive solutions are most welcome by the users. Moreover, our proposal presents the following main novel contributions with respect to other proposals. From the point of view of users, KiReS provides a natural form of interaction through two avatars. Those animated characters are able to attract the user's attention. Looking at one avatar the user can see the exercise he must make and looking at the other he can see how he is doing it. This feature can help him to correct the performing of the exercise when he does not make it properly. Furthermore, the postures that constitute an exercise are visualized at the top of the interface, so the user can figure out how much remains to finish the exercise. Last, KiReS provides also to the user the possibility of review summaries of exercises already made by him. From the point of view of physiotherapists, KiReS allows them to define customized exercises for the users, using for that, pre-defined postures and movements already stored in the system; to create new exercises just by performing them in front of the system and recording them; and to add a test or a visual analogue scale in order to have not only objective information from the exercise execution but also subjective information directly from the user. Moreover, physiotherapists can also analyze data recorded of the users in order to redefine the therapy for those users or to discover situations that present problems for many users. Finally, we want to mention that KiReS considers a broad spectrum of types of exercises as opposed to the majority of proposals that consider fixed exercises to specific physical pathologies; and that we have tested it's suitability in a real scenario.

As a summary, we can say that our goal is, as in some previous works, to try to exploit the potential of Kinect for Windows, a non-wearable device, in the area of telerehabilitation because it is a non-invasive and easy-to-use solution for user interaction. Moreover, in the development of KiReS we have put a special emphasis on achieving that KiReS motivates the user, incorporating a friendly interface that includes motivational features. The use of avatars in

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telerehabilitation systems is highly desirable, successful rehabilitation depends largely on the patient's motivation and compliance with therapy. Also the contributions we have described are oriented to obtain a novel system that outcomes the limitations we have identified in other proposals.

The rest of the paper is organized as follows: In section 2 we describe the overall architecture of the system. In section 3 we provide details on the features provided for the user and in section 4 details on the features provided for the physiotherapist. In section 5 we present briefly some results obtained when operating with KiReS. And finally, in section 6 we present our conclusions.

II. An Overview of KiReS

KiReS is a telerehabilitation system that offers the users and the physiotherapists innovative features by using Kinect as interaction device. The architecture of KiReS is divided into modules and follows a client-server approach. We give in the following a brief overview of the main (communication and database access modules, although they exist in the system, are not described nor shown in Fig. 1). Moreover, it is distinguished between the client of the user and the client of the physiotherapist. Both have the same modules but the functionality supported by its respective interface module is different. User's interaction with the system is done only through Kinect while the physiotherapist can interact with keyboard and mouse and also with Kinect.

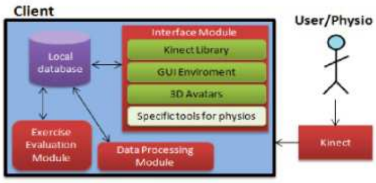

Fig. 1 System architecture

A. Exercise Evaluation Module

This module evaluates performed exercises and sets if they have been properly executed by comparing the results obtained with the expected data.

In rehabilitation therapies, exercises are defined using tables. These tables indicate the members of the body that should be exercised and which movements should be performed. The definition of the exercises in our system is based on this way of working, in order to develop a methodology as close as possible to that followed by physiotherapists in traditional therapies. Exercises consist of a series of movements and these movements are composed of an initial posture, one or more trajectories and a final posture. The postures indicate the beginning and the end of a movement, and the trajectories of the joints indicate the movement itself.

We have developed an exercise recognition algorithm that analyses user movements in three stages, one for each element (initial posture, final posture and the trajectories of the most relevant joints).

B. Data Proccessing Module

This module handles received data from Kinect and creates a descriptor of the user's posture. The skeleton data that Kinect provides is the base of the descriptor. In this skeleton structure each node is a joint of the body. There are a total of 20 joints described by points with 3 coordinates width, height and depth (see Fig. 2). The data received by Kinect about all joints are processed to obtain three types of measures: angles between joints, angles between limbs and, relative positions in the Z axis. With all these measures we define a descriptor of 30 features that gives information about the relative position in 3D and angles formed by the different members of the body (please see in [14] the features of the descriptor).

Fig. 2 Joints of Kinect skeleton

C. Interface Module

As mentioned before, the features of the interfaces designed for users and physiotherapists are different. We show them in section III and IV respectively. However, in both cases, interfaces have been developed using Unity 4 for the 3D environment and all the scripts that control the behavior of the interface were developed in C#. The avatars and the rest of the 3D models were modeled in 3Ds Max and exported to Unity.

Kinect drivers are not directly compatible with Unity, for this reason, an open source dll library has been used for interaction. This library provides basic functionality for Kinect in Unity.

III. KiReS for Users

When displaying the exercises, the interface has to be attractive enough to encourage users to participate in therapy but also simple and clear. The interface module handles the structure and functionality of the provided GUI (Graphical User Interface) and of 3D avatars that show the user how to execute the exercise and the actual execution respectively. Other elements could be incorporated to the interface in order to provide comments and tips for the user.

A. Exercise execution

The interface for exercises execution handles two avatars (see Fig. 3). The one on the left shows to the user the exercise he/she has to execute. This avatar can show the posture that the user has to perform (the initial posture of the

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next movement) or it can show the movement the user has to do. The avatar on the right follows the user and shows the ongoing posture he/she is performing.

The avatar on the left acts as a guide for the user showing the exercise he/she has to do. In the meantime the exercise recognition algorithm analyzes user's posture and movements and updates the avatar on the right and the boxes below to give information.

As Fig. 3 shows, this interface has also in the low part four informative boxes that give specific information to the user. A series is the list of exercises to be done on a session and the repetitions is the number of times an exercise has to be done in each series. The boxes in the first line show the number of series left and the number of repetitions left for the actual exercise respectively. When the user has done all the series of the session the session is finished.

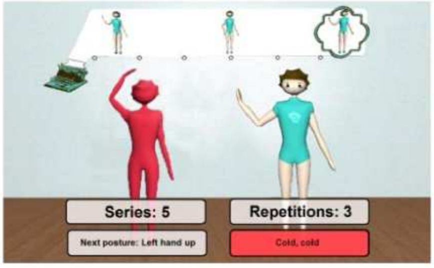

Fig. 3 Performing an exercise of a series

In the second line there are two more boxes. The box on the left shows the name of the next posture the user has to reach. And the one on the right shows the "state" of the actual movement in real time. This box is continuously updated by the exercise recognition algorithm and it displays the info with five different messages:

- "Execute the movement": When the user has reached the initial position and has to execute the movement
- "Execute posture": When the user is very far from reaching the next posture.
- "Cold, cold" (Red box): When the user is about to reach the posture.
- "You're close" (Yellow box): When the user is very close to the posture.
- "Correct!!" (Green box): When the posture is correct.

The avatars and the informative boxes provide feedback to the user. This way the system guides the user in his/her therapy, but also provides a game-like immersive experience that motivates and makes the therapy more enjoyable.

On the top there is a ribbon that shows the exercise as the list of postures that have to be reached in a session. This ribbon is updated as the user completes exercises to show in every moment how many are left.

IV. KIRES FOR THE PHYSIOTHERAPIST

The therapy management tool is specific for the physiotherapist interface. On the one hand, it handles aspects concerning the development of therapies and, on the other hand, it facilitates the task of associating auto tests to therapies. In the following subsections we explain briefly those two aspects.

A. *Therapy management*

When a physiotherapist needs to define a therapy for a user he can use predefined exercises or he can define new ones. In the first case, those exercises had also been defined previously; for that reason, we focus on the task of managing postures, movements and exercises respectively. New postures and movements are added performing them in front of Kinect, after that can be assigned to the new exercises. The interface provides the assistance to create exercises step by step, this way we guarantee that the exercise structure is respected and our recognition algorithm is able to evaluate them.

1) *Posture management*

Posture definition requires fulfilling a simple form giving a name to identify it. A posture is the simplest element of an exercise and therefore necessary for the definition of any other structure.

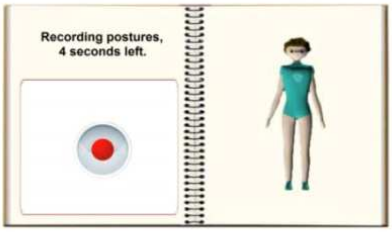

Fig. 4 Posture recording

The physiotherapist performs the posture in front of the system and records it (see Fig. 4). Then, a recording player tools allows him/her to select frame by frame which postures to store from the recording. When storing postures, the posture recognition algorithm analyzes them in order to guarantee that they are similar enough. This way the possibility of adding completely different postures with the same name is avoided. For the best recognition accuracy it's convenient to store at least 6 different examples of a posture.

2) *Movement management*

Movement definition requires assigning at least a name to identify the movement and select the initial and final posture that the movement will have. Once both postures are selected, the system analyzes them. The relevant joints, that best represent the transition from initial posture to final posture, are selected from the posture descriptors. These joints will be recorded and stored to characterize the movement in the next phase.

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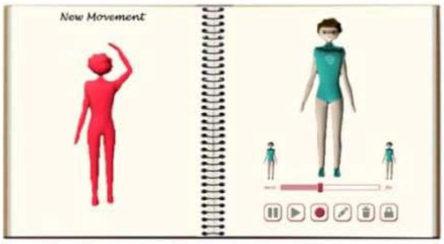

Fig. 5 Movement recording

Movement recording makes use of the same features as posture recording. In this case the physiotherapist selects the movement he/she wants to record and the system shows an interface like Fig. 5. In this interface two avatars are shown. The one on the right is controlled by the therapist. The one on the left shows the therapist the posture he/she must reach. The posture recognition algorithms checks when the therapist makes both the initial and final posture. In the meantime the trajectory of the relevant joints is recorded. After reaching the final posture the recording player tool is available and the therapist can visualize the movement and decide whether to store it or not. It is recommended to perform and record at least 4 times the same movement.

3) *Exercise management*

Exercise definition is made by assigning movements to an exercise. A simple exercise can be made with just one movement but complex exercises are defined as a combination of basic movements, creating a sequence of movements where the final posture of a movement matches the initial posture of the next one.

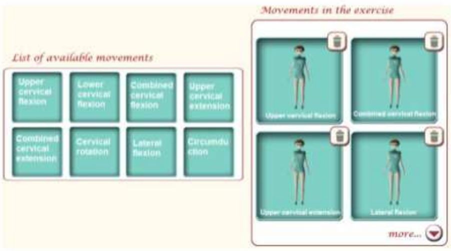

Fig. 6 Exercise definition

The exercise creation interface allows the therapist to define the composition of an exercise. It shows a form to fulfill data of the exercises and two lists (see Fig. 6). The top list contains the movements assigned to that exercise and the bottom list contains the available movements to add. When selecting a movement the system checks if the final posture of the previous movements matches the initial of the new one. If they match the movement is added to the exercise. This is the last step to define a new exercise. Once this is done the exercise will be stored in the system and will be available to add them to a therapy session.

B. *Tests management*

Performance evaluation is an important factor in therapy. Our proposal includes the option of adding two types of subjective evaluation tests, auto tests and visual analogue scale. Users may answer after their session these tests in order to have not only objective information from the exercise execution but also subjective information directly from the user.

1) *Auto tests*

The auto test interface is oriented to create, manage and evaluate auto tests. These auto tests include questions about different aspect of user's daily life and the possible answers are valued differently depending on their severity. We developed an auto test management interface, in order to include these tests in the system. With this tool, the therapist defines the questions of the test and the possible answers with their punctuation. Once the test is defined, the therapist can assign it to a therapy, so that, the user will have to answer the test before ending a session. Test results are automatically generated according to specifications once the user has answered the questions.

For each physical alteration a specific auto test can be defined to accurately measure user's state. Thus, the system lets the therapists add subjective user evaluation to the automatic evaluation of our algorithm.

2) *Visual analogue scale (VAS) for pain*

Another evaluation tool used in physiotherapy that we have incorporated to our system is VAS. The visual analogue scale is a technique used to measure subjective phenomena like pain. It is a self-reporting device consisting of a line of predetermined length that separates extreme boundaries of the phenomenon being measured.

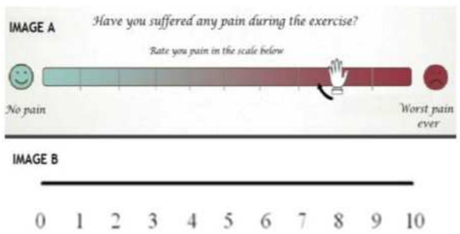

Fig. 7 VAS example

The user sees the image A, on which he/she marks a point on the line between the absence of pain and the worst pain you can imagine. That point is projected on a sliding scale scored from 0 to 10 (image B) that the user will not see (This value may be rounded). Like in auto tests the system lets the therapist to decide when he/she wants to add the pain test with VAS.

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V. Some Performance Results

Since we have developed a functional prototype we made some performance tests in order to analyze the suitability of the system. Using the specific algorithm that we developed for exercise recognition with Kinect, we made some performance tests to measure recognition accuracy and execution time. We have created, with the supervision of physiotherapists, some test and train datasets to evaluate the performance of the algorithms. In the recording of the datasets five volunteers took part. These datasets contain on the one hand, body postures (45 in the train set and 4500 in the test set) and, on the other hand, recordings of rehabilitation exercises (32 recordings in the train set and 48 in the test set). We achieved a 91% accuracy in posture recognition, an 88% accuracy detecting correct exercise executions and a 94% accuracy detecting wrong exercise executions. The previous results are close to those reported in [15] (85% accuracy) or in [16] (91.2% accuracy). Although it is difficult to make an accurate comparison, because the first [15], uses a different device to track movement, and the second [16], is oriented to complex pose comparison in 3D motion data. We cannot compare results with other systems that use Kinect [8-13] because they do not provide performance results. During the tests we also established a threshold value for posture recognition. This parameter is adjustable, therapist could change it to make the system more strict identifying body postures depending on the stage of the therapy.

Considering that user feedback is a key point for a successful rehabilitation, the recognition algorithm should be able to process Kinect data in real time. So we checked whether the algorithm was able to process the data without delays in the system. We found that our algorithm could process more than 20000 postures per frame, which in practice guaranties no perceptible delays (for more details see [17]).

VI. Conclusions

This paper presents the main features of KiReS, a Kinect for Windows based telerehabilitation system. This system is oriented to take advantage of the innovative interaction capabilities of Kinect in order to offer new functionalities for the users but also for the physiotherapists. The different modules of KiReS provide a wide spectrum of functionalities standing out: posture, movement and exercise efficient management; user interaction via Kinect; exercise recognition and evaluation capabilities; and a user friendly interface with 3D avatars.

In order to develop the system and characterize postures, movements and exercises we have worked jointly with physiotherapists. In contrast to other approaches, KiReS is adaptable to different physical treatments. It can be loaded with exercises for a wide variety of physical alterations, giving physiotherapists the opportunity to add themselves new exercises according to their own criteria. We also think that assessment based on scientific methods (combining automatic evaluation with user auto tests) is a point of difference of our proposal.

Additionally the system allows the recording of a great amount of patients' data: exercise executions, therapy evaluations, results of the tests, in summary, the recovery evolution of the users. We believe that these data can be a great source of knowledge for the physiotherapists. That is why in future research we expect to develop a data mining and an automatic therapy planning module to exploit all these data.

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B. Exercise recognition for Kinect-based telerehabilitation

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Exercise Recognition for Kinect-based Telerehabilitation*

D. Antón; A. Goñi; A. Illarramendi

Department of Computer Languages and Systems, University of the Basque Country UPV/EHU,
Donostia-San Sebastián, Spain

Keywords
Telerehabilitation, telemedicine, exercise recognition, Kinect-based motion tracking

Summary

Background: An aging population and people's higher survival to diseases and traumas that leave physical consequences are challenging aspects in the context of an efficient health management. This is why telerehabilitation systems are being developed, to allow monitoring and support of physiotherapy sessions at home, which could reduce healthcare costs while also improving the quality of life of the users.

Objectives: Our goal is the development of a Kinect-based algorithm that provides a very accurate real-time monitoring of physical rehabilitation exercises and that also provides a friendly interface oriented both to users and physiotherapists.

Methods: The two main constituents of our algorithm are the posture classification method and the exercises recognition method. The exercises consist of series of movements. Each movement is composed of an initial posture, a final posture and the angular trajectories of the limbs involved in the movement. The algorithm was designed and tested with datasets of real movements performed by volunteers. We also explain in the paper how we obtained the optimal values for the trade-off values for posture and trajectory recognition.

Results: Two relevant aspects of the algorithm were evaluated in our tests, classification accuracy and real-time data processing. We achieved 91.9% accuracy in posture classification and 93.75% accuracy in trajectory recognition. We also checked whether the algorithm was able to process the data in real-time. We found that our algorithm could process more than 20,000 postures per second and all the required trajectory data-series in real-time, which in practice guarantees no perceptible delays. Later on, we carried out two clinical trials with real patients that suffered shoulder disorders. We obtained an exercise monitoring accuracy of 95.16%.

Conclusions: We present an exercise recognition algorithm that handles the data provided by Kinect efficiently. The algorithm has been validated in a real scenario where we have verified its suitability. Moreover, we have received a positive feedback from both users and the physiotherapists who took part in the tests.

Correspondence to:
D. Antón
Department of Computer Languages and Systems
University of the Basque Country UPV/EHU
Pº Manuel Lardizabal, 1
Guipuzcoa
20018 Donostia-San Sebastián
Spain
E-mail: david.anton@ehu.es

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1. Introduction

An aging population and people's higher survival to diseases and traumas that leave physical sequels are challenging aspects in the context of an efficient health management. Telemonitoring technologies have been proposed as a solution to reduce hospital overloads, and using such technologies data can be accessed remotely by healthcare professionals through the Internet and mobile devices [1]. In the area of physiotherapy, telerehabilitation systems that support physiotherapy sessions at home could help reduce healthcare costs while also improving the quality of life of the users that need rehabilitation. Cost containment in health care while trying to maintain access to quality services has become essential in the last years, as we face an aging population [2].

Telerehabilitation should not be seen as a technology in itself, but as the use of new technologies to improve and optimize both rehabilitation services and patient outcome with the idea of reinforcing traditional rehabilitation [3]. Several studies have demonstrated that virtual interaction can be as effective as traditional treatments [4, 5]. Furthermore, the use of telerehabilitation systems with motion capture has been shown to increase the intensity of rehabilitation and enhance user experience [4, 6].

The core technology of our telerehabilitation system is Kinect, an innovative motion capture device developed by Microsoft [7] and PrimeSense. In the specialized literature we can find works that suggest that Kinect can validly assess kinematic strategies of postural control such as [8]. There are also works [9, 10] that suggest that the validity of Kinect posture estimation is comparable to more established techniques for posture estimation from 3D motion capture data. Kinect allowed us to create an innovative telerehabilitation system that can automatically evaluate user's exercises by recognizing user's movements.

The focus of this paper is the algorithm that recognizes and evaluates the therapeutic exercises. We present how exercises are described and how they are recognized. We also introduce some performance results that show the good behavior of the proposed algorithm.

This paper is organized as follows: In section 2 we describe some previous works done in this field. Next, in section 3 we explain the main features of the methods that constitute our algorithm. In section 4 we present the datasets used for the experiments and some initial considerations related to them, and in section 5 the results obtained. Finally, in sections 6 and 7 we present the discussion and some conclusions respectively.

2. Background

Telerehabilitation systems can be found both in an academic setting as in a commercial environment. If we analyze their evolution we can observe that some of them make use of wearable devices (e.g. [11, 12]). In [11] Llorens et al. present Biotrack, a system for task-oriented games that evaluates whether people with cognitive impairment can reach some predefined locations. To that end, the system makes use of markers attached to the user's body and infrared cameras. In [12] the authors use smartphone's build-in inertial sensors to monitor exercise execution and to provide acoustic feedback on exercise performance and execution errors. However, a trend is seen nowadays for the use of low-cost non-intrusive tracking devices such as Nintendo Wii Remote or Kinect in the telerehabilitation systems. In [13] the authors describe a telerehabilitation system, based on Nintendo Wii Remote, which uses an accelerometer to record the user´s movements in 3D. The system focuses on rehabilitation exercises of upper limbs. Among the proposals that use Kinect two groups can be distinguished: proposals that make use of Kinect for Xbox; and those that make use of Kinect for Windows. Among the works of the first group we can mention [14–16]. In [14] the authors present a prototype of a game-based telerehabilitation system with Kinect that they have developed. However, their main goal is to prove the adequacy of using Kinect for telerehabilitation therapies and so they do not show technical details about the recognition method. In [15] Kinerehab is presented, an occupational therapy system based on Kinect, where users can perform three different exercises: lift arms front, lift arms sides and lift arms up. Finally, in [16] they present 21 game concept prototypes which receive and process data sent by Kinect but the authors do not deal with the evaluation. Concerning the works that use Kinect for Windows we can find, on the one hand, commercial products such as [17, 18] which do not show many technical details concerning their internal behavior. On the other hand, there are research proposals that focus on different pathologies, such as [19] which focuses on patients with traumatic brain injury, [20, 21] which are oriented to upper limb rehabilitation, and [22] which is focused on full body gait analysis. Moreover, we want to mention the system presented in [23], which explores the combined use of inertial sensors and Kinect. They made an evaluation of different exercises (shoulder abduction and adduction, squat and sit to stand), but their goal was more aimed at performing online calibration of sensor errors than the evaluation of the exercises.

Our proposal advocates for the use of Kinect, and in this paper, we focus on the core exercise recognition algorithm of our telerehabilitation system. Next, we mention the main characteristics that distinguish it from other proposals from three different perspectives.

1) *From the users' point of view*, the algorithm provides visual and acoustic feedback about the exercises performed so that users can see, through avatars, how they are doing the exercises and how the therapist performed them (►Figure 1). They can also see the number of series that remain to perform and also the number of remaining repetitions for the actual exercise respectively. Moreover, when the user reaches the final posture, an acoustic signal is provided together with information

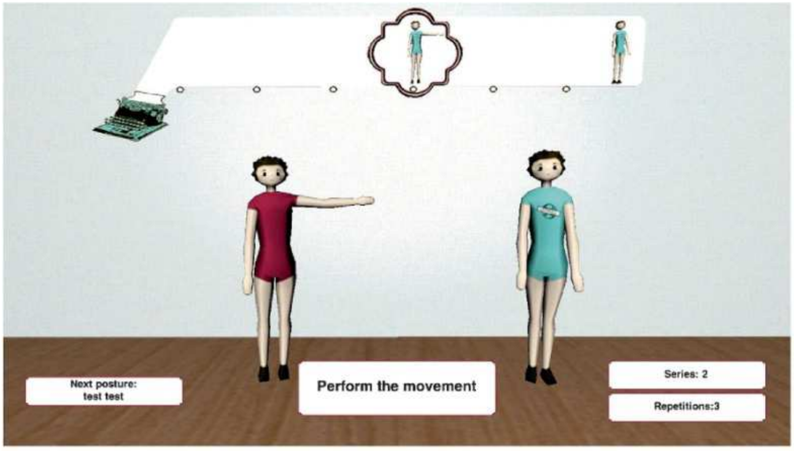

Figure 1 Rehabilitation session

about the speed of execution (adequate, too fast or too slow).

2) *From the therapists' point of view*, the algorithm allows them to define exercises for the users by a) using exercises already stored in a library, b) combining those stored exercises, or/and c) defining new customized exercises simply by recording them in front of Kinect. The way exercises are recorded and stored facilitates their exchange among different therapists. Furthermore, therapists can reproduce in their computers the sessions that users have made at their homes. The general idea is to mimic their usual way of working (▶ Figure 2).

3) *From the technical point of view*, we want to mention three main features, a) an *efficient* real-time execution, so users get on-line feedback; b) a *good accuracy* when recognizing exercises; and c) *flexibility* when adapting itself to the user's body movement limitations at each moment. The algorithm not only considers final snapshots of the exercises performed but also intermediate snapshots during executions, which means that the goal is not only to identify the final posture but also how well the user gets to it.

Finally, the algorithm has been validated with data taken from volunteers. Those data are available in http://bdi.si.ehu.es/bdi/members/david-anton/research-resources/. Moreover, it has also been tested with real users. In both cases, the algorithm provides good accuracy at recognizing exercises.

Figure 2 Therapist's datebook

3. Methods

In this section, we first show the descriptor that models body postures and the method used to classify those postures. Then we present the main features of the exercise recognition method.

3.1 The Descriptor of Postures

Kinect is a visual tracking system without markers that allows users to control and interact with applications through an interface that can recognize gestures, voice commands and objects. Kinect provides a skeleton structure in which each node is a joint in the body. The skeleton contains a total of 20 joints described by 3D points. These points are referenced in a coordinate system (axes X, Y and Z) whose origin is at the center of the plane parallel to the captured image and intersecting with the Kinect camera. The coordinates obtained from Kinect are translated to another coordinate system whose origin is at the hip center of the user so that relative position between the camera and the user does not influence the exercise recognition. Those translated coordinates are used to calculate the following three types of measurements: 1) Relative positions of some parts of the body in the Z axis. A volume around the user is defined by two values, a minimum and a maximum distance in the Z axis, and two binary features for each joint are generated: one that takes the value 1 or 0 depending on whether the Z coordinate of a joint is above the minimum, and the other one that takes the value 1 or 0 depending on whether the Z coordinate of a joint is below the maximum. 2) Angles between joints. They are the angles between the lines formed by two joints, relative to the origin of coordinates located at the first one of them and 3) Angles between limbs. They are the angles between two limbs connected by a joint.

With these values we define a posture descriptor that reduces significantly the dimensionality of the data. We obtain a simplified representation of a body posture that still encompasses sufficient information for the recognition process as we show in Section 5. The posture descriptor has a total of 30 features, divided in two distinct parts (▶ Table 1), 18 binary features (from 1 to 18) that give information about the relative position in 3D of some joints (neck, hands, shoulders, knees and feet) and 12 features that represent the angles formed by the different parts of the body projected in the frontal plane (XY) (from 20 to 24 and from 26 to 30) and in the lateral plane (XZ) (19 and 25).

3.2. Posture Classification Method

Once a posture is captured and its corresponding descriptor is created, the next step is to classify it. Classification is made by comparing the captured descriptor with previously annotated posture descriptors. In order to compare two posture descriptors D_i and D_j, a similarity measurement, $dist(D_i, D_j)$, based on the distance between them is used:

$$dist(D_i, D_j) = angDif(D_i, D_j) * (1 + binDist(D_i, D_j)) \quad (1)$$

As mentioned before, the descriptor is composed of two parts: on the one hand, a set of 18 binary features and, on the other hand, 12 angular measurements of body members. The two parts of the descriptor ($binDist(D_i, D_j)$ and $angDif(D_i, D_j)$) are evaluated independently, by using formulas

Table 1 Variables of the posture descriptor

Binary	1	2	3	4	5	6
	NeckMin	NeckMax	RHandMin	RHandMax	LHandMin	LHandMax
	7	8	9	10	11	12
	RShoulMin	RShoulMax	LShoulMin	LShoulMax	RKneeMin	RKneeMax
	13	14	15	16	17	18
	LKneeMin	LKneeMax	RFootMin	RFootMax	LFootMin	LFootMax
Angles	19	20	21	22	23	24
	NeckZ	NeckX	RElbow	LElbow	RShoul	LShoul
	25	26	27	28	29	30
	ColmZ	ColmX	RThigh	LThigh	RLeg	LLeg

based on the sum of absolute errors of their corresponding descriptor features:

$$binDist\left(D_i,D_j\right)=\sqrt[2]{\sum_{k=1}^{18}\left|D_i(k)-D_j(k)\right|} \quad (2)$$

$$angDif\left(D_i,D_j\right)=\sum_{k=19}^{30}\left|D_i(k)-D_j(k)\right| \quad (3)$$

where $D_x(k)$ is the feature k of descriptor D_x, and the results are combined to obtain a measurement of similarity between postures (see right part of ►Equation 1).

To classify a new posture descriptor, a search is applied sequentially on the set of all previously recorded and annotated posture descriptors. If the distance between the posture descriptor to be classified and the annotated posture descriptors is less than a threshold value pth_0, then the corresponding class is assigned[a]. If there is none, then the posture is classified as "unknown".

[a] When different posture classes could be assigned, the one with the smallest distance between the posture descriptor to classify and the annotated posture descriptor is in fact assigned.

It is quite obvious that the lower the threshold value pth_0, the greater the similarity between the compared posture descriptors must be. In the event that pth_0 were 0, then the user must perform a posture that is exactly the same as one that has been previously recorded in order to be classified as that. However, it must be noticed that there are different descriptors annotated with the same posture class. Therefore, using a threshold $pth_0 = 0$ may be not appropriate when the performed posture descriptor is not exactly equal to any of the recorded ones but is definitely of that posture. On the contrary, greater values for the threshold would make a posture descriptor be misclassified. In section 5.1.1 we show which is the optimal value obtained for this trade-off value that is pth_0.

3.3 Exercise Recognition Method

In rehabilitation therapies, exercises usually consist of series of movements. Each movement is composed of an initial posture, a final posture and the angular trajectories of the limbs involved in the movement (the relevant limbs). Both the initial posture and the final posture of a movement are identified with their respective descriptors. The movement between the initial and final posture is represented by sequences of angular values taken from the limbs that are in a different position from one posture to another (it is assumed that the limbs whose positions are equal in the initial and in the final postures do not move during the transition). Complex exercises are defined as a combination of basic movements, creating a sequence of movements where the final posture of a movement matches the initial posture of the next one.

3.3.1 Identification of the Initial Posture

When starting a movement the system waits for the user to get into the initial posture. The posture classification method checks the user's current posture until it identifies it as the initial one. These checks are performed in real-time at a rate of about 30 checks per second which is the frequency with which Kinect provides data. When the initial posture is identified the system starts the trajectory recognition.

3.3.2 Trajectory Recognition

The trajectory recognition method has as a main purpose to recognize if the movement itself is well performed. During the recognition, the trajectory of each relevant limb i involved in the movement is compared to the trajectory of the same limb stored for that movement and a similarity value v_i is obtained based on distances between them. If the distance is less than a threshold value $trth$ the trajectory path is considered to be correct, and incorrect in opposite case.

Another important aspect here related with the goal of recognizing trajectories in real-time is the frequency of the trajectory recognition or, in other words, how often this comparison among performed and stored trajectories has to be executed. Taking into account that trajectory recognition in real-time is a requirement, it is not pos-

Table 2 Training and test sets composition for postures

Label	N°	Label	N°
Neutral	6	Unknown	1090
HeadLeft	5	Neutral	1253
HeadRight	5	HeadLeft	248
HeadForward	5	HeadRight	337
RHandUpLeft	8	HeadForward	326
RHandDownLeft	8	RHandUpLeft	446
RHandUpBack	8	RHandDownLeft	346
Total	**45**	RHandUpBack	454
		Total	**4500**

sible to compare the completely performed and stored trajectories only once at the end. For that reason, we also introduced partial trajectory recognition analysis. Therefore, our trajectory recognition method periodically compares for each limb, the trajectory path performed up to that moment by the user with the corresponding stored trajectory. And, as the user may have not finished the movement completely, a last comparison with the complete stored trajectory also has to be executed. In summary, a two-phase analysis takes place: an analysis of partial trajectories and an analysis of the complete trajectory. The trajectory is classified as incorrect when either some[b] partial trajectories or the complete one is incorrect, and as correct in opposite case. In section 5.1.2 we explain how we have obtained the trth trade-off value. Notice that this method is able to detect incorrect trajectories in real-time and can indicate to the user which limb position must be corrected.

In order to calculate the distances among trajectories, the values, we use a variant of the Dynamic Time Warping (DTW) algorithm (please refer to [24] for detailed information on DTW). Although other alternative techniques such as Hidden Markov Models (HMM) have been extensively used for gesture recognition, we chose the DTW technique after analyzing some works that compare their behavior [25–27] and finding that it allows us to: 1) deal with a much smaller training set [25]; 2) not have to re-train a model after a new movement is recorded, an advantage that makes the recording of exercises clearer, simpler and faster for the physiotherapist; and 3) analyze the data in real-time as its performance is high enough [26] for the analysis of exercises.

3.3.3 Identification of the Final Posture

While analyzing the trajectories, the exercise recognition method also checks the posture of the user. When the final posture is identified the movement is finished. If an exercise has more movements the method tries to identify the initial posture of the next movement.

Identifying the final posture has a peculiarity given the context of rehabilitation. In some stages of therapy what is expected from the user is to try to reach that position or, at least, to make the physical effort to reach it. Assigning adequate exercises is the physiotherapist's decision but we also considered a "reach and hold" objective for the patient. Thus, the method adapts the threshold depending on the time spent performing the movement. The initial threshold pth_0 is multiplied by a flexibility factor ff that makes the algorithm be less rigid in posture classification. That is to say that the new threshold value is $pth = pth_0 * ff$. The flexibility factor *ff* is a function that depends on the time spent t and the time t_r in which the movement was recorded, $ff = 1 + \alpha \lfloor t/t_r \rfloor$ where α could be adjusted by the therapists (α = 0 means no flexibility at all).

Table 3 Training and test sets composition for trajectories

Label	N°	Label	Corr	Incor
ToHeadLeft (THL)	4	THL	4	4
ToHeadRight (THR)	4	THR	4	4
ToHeadForward (THF)	6	THF	4	4
ToRHandUpLeft (TRHUL)	6	TRHUL	4	4
ToRHandDownLeft (TRHDL)	6	TRHDL	4	4
ToRHandUpBack (TRHUB)	6	TRHUB	4	4
Total	**32**		**24**	**24**

3.3.3 Exercise Rating

When the user has completed a movement, the method analyzes the result and rates the overall performance. This rate r is calculated from the values obtained for each relevant limb (as explained in section 3.3.2) with the following formula:

$$r = \sqrt[2]{v_1^2 + v_2^2 + \ldots + v_n^2} \qquad (4)$$

where n is the total number of relevant limbs analyzed. Although the flexibility factor *ff* does not appear explicitly in the formula, the rate r takes it into consideration implicitly, because v_i values will be greater when the final posture is not performed exactly. Finally, the overall exercise rating is the average of the r rates

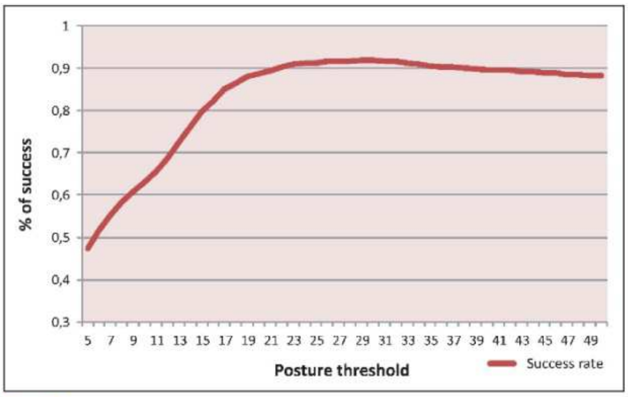

Figure 3 Descriptor classification accuracy depending on threshold

[b] If the recognition method were too strict, then just one punctual incorrect partial trajectory would lead to classify it as incorrect. However, we think that is better to be more flexible and wait to see if the following ones are also incorrect or not.

Table 4 Posture confusion matrix for threshold 30

Posture	Unk	Neu	HL	HR	HF	RHUL	RHDL	RHDA	Total
Unknown (Unk)	802	165	20	18	34	9	29	13	1090
Neutral (Neu)	29	1223	0	1	0	0	0	0	1253
HeadLeft (HL)	0	0	248	0	0	0	0	0	248
HeadRight (HR)	2	0	0	335	0	0	0	0	337
HeadForward (HF)	0	0	0	0	326	0	0	0	326
RHandUpLeft (RHUL)	33	0	0	0	0	413	0	0	446
RHandDownLeft (RHDL)	5	0	0	0	0	0	341	0	346
RHandUpBack(RHUB)	5	0	0	0	0	0	0	449	454

of all the movements that compose the exercise.

4. Setting up the Experiments

We conducted several tests to check the reliability of the algorithm when identifying postures and exercises, as well as to verify that it was capable of processing data in real-time. Moreover, an important issue was to obtain an efficient algorithm with few reference examples. This would allow the physiotherapists to add new exercises by introducing some examples in the system using Kinect.

Being Kinect for Windows a recent device and telerehabilitation a very specific area we have not found any database of recorded postures or exercises. For that reason, we created, with the supervision of physiotherapists, some datasets to validate the performance of the algorithm. Moreover, a physiotherapist recorded the postures and movements for the clinical trials.

4.1 Algorithm Validation Set-up

The datasets created to validate the algorithm contain body postures and recordings of some rehabilitation exercises. In particular, the recorded exercises are part of two therapy protocols. One is oriented to cervical disorders and the other one is oriented to shoulder disorders. These protocols describe with detail the rehabilitation phases and exercises adequate for each treatment. We used six exercises to test our algorithm (The specifications and the execution descriptions of the exercises can be found in this URL[c]).

Five healthy volunteers (3 male and 2 female) with ages from 25 to 58 took part in the recording of the above mentioned exercises. Using the resulting data, posture descriptors were annotated manually with each corresponding posture class (seven known posture classes and another one for unknown postures). Those annotated descriptors constituted the test dataset of 4500 different posture descriptors. In addition to this dataset, a training set was created which has 45 posture descriptors labeled with the previous 7 known classes. ►Table 2 shows the distribution of the posture descriptors on each of the datasets.

To measure the time performance we needed datasets with different sizes. We used six datasets with 45, 4500, 15,000, 20,000, 35,000 and 45,000 posture descriptors respectively in order to perform time measurement tests. The last four datasets are synthetic sets created by repeating the descriptors in the dataset with 4500 descriptors.

We also created two datasets to carry out the trajectory tests. One was used as training set that contained 32 correctly performed trajectories, and the other one was used as test set that contained 48 trajectories, 24 correct and 24 incorrect (►Table 3).

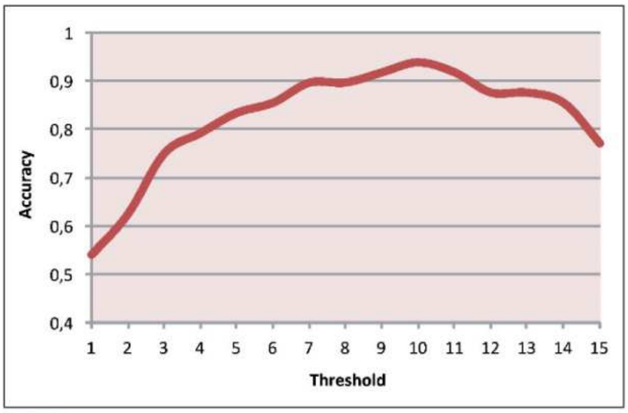

Figure 4 Trajectory classification accuracy depending on threshold

4.2 Clinical Trials Set-up

In order to prepare the clinical trials two main tasks took place, the recording of exercises and the selection of real users. With regard to the first task, a physiotherapist recorded a set of exercises to be executed by real users with shoulder disorders. She recorded 8 postures and 6 movements (these 6 movements where reversed making a total of 12 movements) and using our managing tool she combined them into 6 different exercises. The recorded movements plus the reversed version of them were the following: shoulder abduction (1–2), hands to mouth (3–4), shoulder extension (5–6), shoulder flexion (7–8),

[c] http://bdi.si.ehu.es/bdi/members/david-anton/research-resources/

hands to head (9–10), and shoulder rotation (11–12). These recordings were considered as the *ground truth* for our algorithm.

With regard to the second task, 15 real users suffering from shoulder disorders were selected to take part in two trials (7 in the first trial and 8 in the second one). They had an average age of 66 in a range from 44 to 83 and they had been doing rehabilitation sessions for at least one month.

Table 5 Partial trajectory analysis accuracy

	Ident. as correct	Ident. as incorrect
Correct trajectories	91.67%	8.33%
Incorrect trajectories	12.50%	87.50%

Table 6 Complete trajectory analysis accuracy

	Ident. as correct	Ident. as incorrect
Correct trajectories	100%	0%
Incorrect trajectories	33.33%	66.67%

Table 7 Overall trajectory analysis accuracy

	Ident. as correct	Ident. as incorrect
Correct trajectories	91.67%	8.33%
Incorrect trajectories	4.17%	95.83%

5. Experimental Results

In this section we present the experimental results that helped us, on the one hand, to tune the exercise recognition method and, on the other hand, to validate it in clinical trials.

5.1 Tuning the Exercise Recognition Method

In this subsection we explain how the previously mentioned pth_0 and $trth$ thresholds were calculated and the feasibility of the real-time processing.

5.1.1 Posture Threshold pth_0

As stated in section 3.2, the optimal value for the pth_0 must be empirically found. A series of tests were conducted with threshold values between 5 and 50 to assess which of them gave the best results. The 4500 posture descriptors of the test set were classified with different threshold values. The results showed that the maximum is reached on threshold $pth_0 = 30$ with an accuracy of 91.9% and that with higher threshold values accuracy slowly decreases as shown in ►Figure 3. As pth_0 is a trade-off value, then greater or lower values decrease accuracy, but in a different way: with greater values “unknown” posture descriptors are classified as known postures, but with lower values some of the known postures are classified as “unknown”.

The confusion matrix in ►Table 4 provides more detailed information of these results for the optimal threshold value 30. Each element indicates the number of times the posture of the row has been classified as the posture of the column. The posture descriptors labeled as “unknown” are mostly transitional, undefined postures that occur when moving from one known posture to another.

Notice that most classification errors for unknown postures are produced because they are classified as “neutral” postures. The “neutral” posture is present in all the exercises analyzed, making the transition to it very common.

5.1.2 Trajectory threshold $trth$

We calculated the trajectory threshold using a similar procedure to the one used for the posture threshold. A series of tests were conducted with threshold values between 1 and 15. The 48 trajectories of the test set were classified with different threshold values. The results showed that the maximum is reached on threshold $trth = 10$ with an accuracy of 93.75%, as shown in ►Figure 4. With higher threshold values the accuracy decreases because more incorrect trajectories are classified as correct.

Nevertheless, as mentioned in section 3.3.2, a trajectory is classified as correct or incorrect after applying a two phase analysis: a partial trajectory analysis and a complete trajectory analysis. In ►Table 5, we show the accuracy results obtained after applying the partial trajectory analysis using threshold $trth = 10$ (where global accuracy is 89.58%). It´s important to remember that trajectories classified as incorrect during the partial trajectory analysis are definitely[d] classified as “incorrect”.

[d] For this analysis, we have assumed that an incorrect partial trajectory has to be recognized as incorrect for at least 1.5 seconds in order to be definitely classified as incorrect.

Table 8 Trajectory confusion matrix for threshold $trth = 10$

	THL		THR		THF		TRHUL		TRHDL		TRHDA	
	Cor	Inc	Cor	Inc	Cor	Inc	Cor	Inc	Cor	Inc	Cor	Inc
Cor	4	0	4	0	4	0	4	0	3	1	3	1
Inc	0	4	0	4	0	4	0	4	0	4	1	3
Tot	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**3**	**5**	**4**	**4**

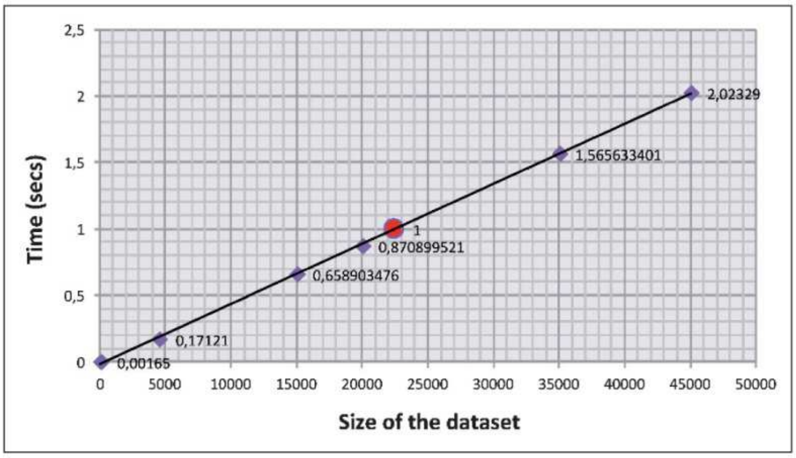

Figure 5
Average time to process 30 descriptors per dataset

The trajectories classified as "correct" by using the partial trajectory analysis do still have to pass the complete trajectory analysis. After that, as can be seen in ►Table 6 all the correct trajectories are again (and definitely) classified as correct by the complete trajectory analysis, and 66.67% of the remaining incorrect ones are now well classified.

In ►Table 7, we can see the overall trajectory analysis accuracy results corresponding to the combined method of partial and complete trajectory analysis that provides a global accuracy of 93.75%, and in ►Table 8 the detailed confusion matrix can be observed.

5.1.3 Testing Real-time processing

Previously, we stated that the proposed algorithm should be able to process Kinect data in real-time in order to give feedback to the user as s/he was performing the exercise. Kinect provides 30 frames per second so the algorithm had to analyze 30 skeletons in less than a second to avoid execution delays. Posture analysis, which is done continuously, also implies generating the corresponding descriptors to compare with those already stored.

In order to obtain the processing time and establish how many postures can be processed in real-time, we conducted some tests with different dataset sizes.

The tests for time measurement involved loading six datasets with, 45, 4500, 15,000, 20,000, 35,000 and 45,000 posture descriptors respectively.

In ►Figure 5 we can observe the average time (in seconds) to process 30 unknown posture descriptors against each of the datasets. The linear regression fits the

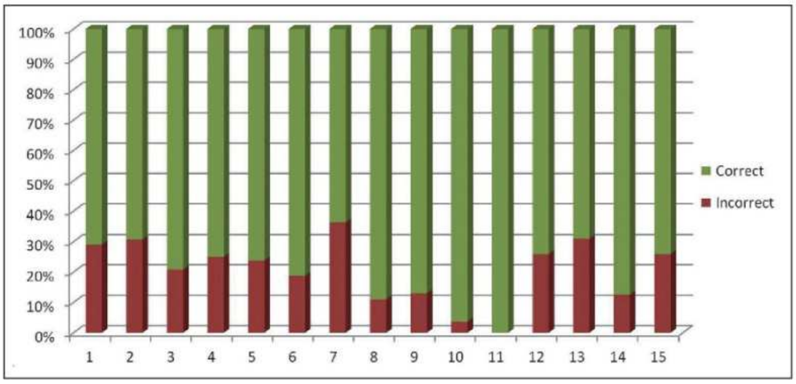

Figure 6
Proportion of correct executed exercises by user

data obtained well, so it´s safe to say that the time required to process a posture descriptor increases linearly with the size of the dataset. According to these results the size limit beyond which it would not be feasible to process a dataset in real-time would be around 22,000 posture descriptors, what ensures that it is possible to manage an adequate number of postures in this context.

With respect to the real-time processing of trajectories, as mentioned before, the DTW algorithm is applied. According to [26] it is possible to process more than 10,000 time series in real-time using DTW. In our case, we have just confirmed that it is possible to process the time-series of all the limbs with a frequency of 30 times per second which corresponds to the maximum quantity of data that Kinect can provide. However, through these experiments we also found that using a frequency greater than 3 times per second did not produce significant changes in the results given by the DTW trajectory analysis.

5.2 Exercise Validation with Clinical Trials

In this subsection we show the results obtained from two trials we did in a rehabilitation center managed by Matia Foundation [28]. First of all, we present the dataset used in order to validate the exercise recognition method. After that we present the accuracy of the method when recognizing movements and exercises performed by the users.

The two trials were supervised continuously by physiotherapists that assessed the correct or incorrect execution of the exercises. Therefore, a dataset of annotated exercises was built. While analyzing the execution of the users we found that on average they made 19% of the exercises incorrectly. In ►Figure 6 the error distribution for each of them is shown. In particular, users 10 and 11 highlight over the others because they get the highest rate of correct execution (96.30% and 100% respectively). These patients had been in rehabilitation for longer than any other. In the opposite side we can highlight patient 7, who could not see the screen well and did not follow the guidance that the 3D avatar provided. In total these patients completed 559 movement executions.

Once the test set was built, the validation of the recognition algorithm was conducted. In the following paragraphs we present the accuracy results grouped by: a) movement; b) exercise; and c) user.

The average recognition accuracy was 95.16%. Out of the all of the correctly executed movements, 97.12% were recognized as correct, but the rate decreases to 86.91% when classifying incorrect movement as incorrect. Moreover, in ►Figure 7 (graph on the left) we can observe that accuracy of Mov4 and Mov10 is 58.32% and 75% respectively. This is because Mov4 and Mov10 are influenced by their initial postures which require lifting the arms towards the head, and in these postures Kinect has difficulties finding joint positions and produces noise in the data. For all other movements the accuracy was above 85%

We want to mention that, for exercise 5 (►Figure 7, graph on the right) the accuracy was significantly lower (81.23%), due to the fact that movements Mov4 and Mov10 are part of this exercise.

Finally, while analyzing the accuracy results for each user (►Figure 8 we show the accuracy distribution for the users of the second trial) we found that, in general, the average accuracy was consistent with the previous results. However, there was an exception, user 13 (with a 75% accuracy) was wearing a loose blouse that made it difficult for Kinect to recognize joints correctly.

6. Discussion

Several works have documented the effectiveness of using different kinds of telerehabilitation systems at home [4–6]. The current trend is oriented towards the development of systems that make use of non-invasive devices and, in particular, the core device of many proposals is Kinect for Windows [17–21], because it is a low-cost portable tracking alternative which does not require users to wear specialized equipment for tracking. A limitation that Kinect presents is that skeleton recognition works well when the user is facing the device, but lateral recognition is not accurate.

Developing a complete functional telerehabilitation system based on Kinect has revealed some important considerations. For the system to be easily adopted by

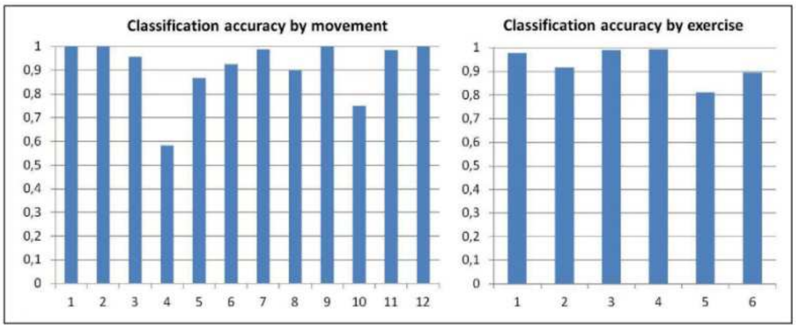

Figure 7
Recognition accuracy by movements and exercises

users, it must provide an interface that users find fun and at the same time allows them to notice the errors they make and their progress throughout the treatment. In this sense, the interface provided by our system includes motivational features such as two 3D avatars that show the user how to execute the exercises and the actual execution respectively (so she/he can be aware of the differences). Moreover, the interface also includes some elements that provide information about the ongoing therapy session. With this interface we realized that the system empowers and keeps the user aware of his/her therapy, but also provides a game-like immersive experience that motivates and makes the therapy more enjoyable.

From the point of view of therapists, after having worked with them closely, we realized that they appreciate the fact that the system follows the guidelines of their usual way of working and so our interface presents a menu as a datebook that shows information in it. Moreover, a relevant issue is the way new exercises are added to the system. The proposed system can be loaded with exercises for a wide variety of physical alterations. The system allows therapists to perform and record the new exercises themselves. In addition to recognizing exercises, the data gathered by our proposal can be used for other purposes in the context of telerehabilitation.

From the data provided by Kinect we have shown that it is possible to develop an efficient and reliable exercise recognition algorithm.

In the clinical trials, we obtained 95.16% accuracy in exercise recognition. There is no reference benchmark to make an accurate comparison with other recognition algorithms. However, our accuracy results are comparable to those obtained by other works that provide solutions in the rehabilitation area. Among them, we can mention [12, 22, 29]. In [12] Spina et al. reported a 96.7% accuracy but using a smartphone's build-in inertial sensors to monitor exercise execution. In [22], Gabel et al. present a gait analysis system based on Kinect sensor that provides correlation coefficients between the Kinect-based prediction and the true value greater than 0.91 for both arms. In [29], the authors present a system for cognitive rehabilitation that achieves a successful monitoring percentage of 96.28%.

Regarding the clinical trials we consider that the collaboration with the Matia Foundation gave us a relevant insight of our proposal, not only for the results obtained in exercise recognition, but also for the experience with the physiotherapists and the patients that took contact with our system. In these medical trails patients did a 19% of the exercises wrong. It seems to be a high rate of failure, but we want to highlight that for all of them it was the first time interacting with Kinect and also that our patients were elderly people not used to interacting with computers.

7. Conclusion

In this paper we have presented a Kinect-based algorithm for the monitoring of

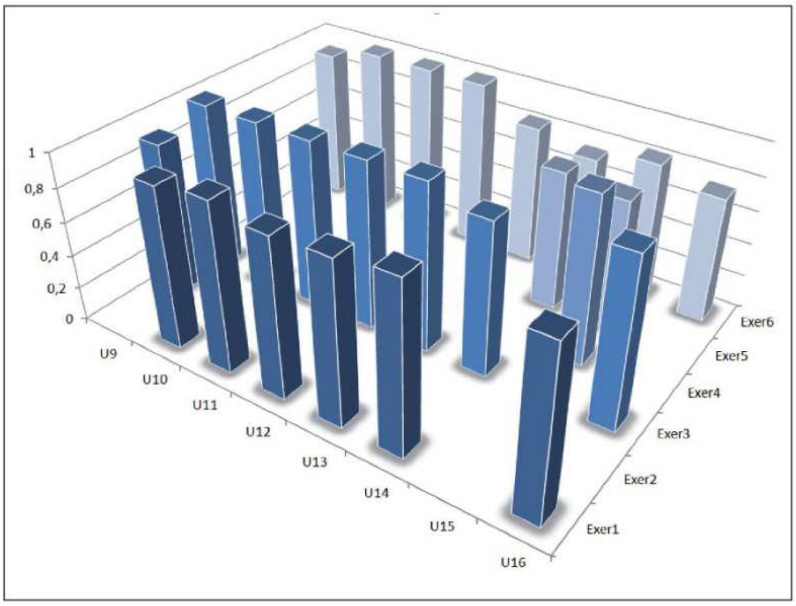

Figure 8 Exercise recognition accuracy by user

physical rehabilitation exercises. That algorithm recognizes the main components of the exercises, postures and movements in order to assess their quality of execution. Furthermore, the friendly interface that it supports provides end users with a game-like immersive framework. This framework motivates them and makes the rehabilitation sessions more enjoyable while at the same time it allows users to be aware of their progress. Moreover, using that interface the physiotherapists can define in an easy way a great variety of exercises customized for users. With respect to technical issues, the algorithm is capable of making real-time recognitions of the exercises and, furthermore, its behavior is good using only a few samples in the training step. Finally, the feasibility of the algorithm has been validated in a real scenario with 15 users achieving a monitoring accuracy of 95.16%. This performance was considered very adequate by the physiotherapists that supervised the clinical trials. In future research we expect to analyze our algorithm using the upcoming version of Kinect and to develop a data mining module to exploit the raw data gathered by the system in order to extract meaningful and actionable information for the physiotherapists and users.

Acknowledgments

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C. Validation of a Kinect-based telerehabilitation system with total hip replacement patients

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Validation of a Kinect-based telerehabilitation system with total hip replacement patients

David Antón[1], Mark Nelson[2], Trevor Russell[3], Alfredo Goñi[1] and Arantza Illarramendi[1]

Abstract

The evolving telecommunications industry combined with medical information technology has been proposed as a solution to reduce health care cost and provide remote medical services. This paper aims to validate and show the feasibility and user acceptance of using a telerehabilitation system called Kinect Rehabilitation System (KiReS) in a real scenario, with patients attending repeated rehabilitation sessions after they had a Total Hip Replacement (THR). We present the main features of KiReS, how it was set up in the considered scenario and the experimental results obtained in relation to two different perspectives: patients' subjective perceptions (gathered through questionnaires) and the accuracy of the performed exercises (by analysing the data captured using KiReS). We made a full deployment of KiReS, defining step by step all the elements of a therapy: postures, movements, exercises and the therapy itself. Seven patients participated in this trial in a total of 19 sessions, and the system recorded 3865 exercise executions. The group showed general support for telerehabilitation and the possibilities that systems such as KiReS bring to physiotherapy treatment.

Keywords

Telerehabilitation, Kinect, eHealth, hip replacement, physiotherapy

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Introduction

Total Hip Replacement (THR) is a common surgery in many countries. For example, the Agency of Healthcare Research and Quality (USA) reports that more than 285,000 THRs are performed each year in the United States. This number is forecast to double in the next 20 years.[1]

Following surgery, rehabilitation is a critical component for resuming normal activities of daily living. Maire et al.[2] indicate that improvement in physical fitness and functional status as a result of rehabilitation is associated with better health status after hip replacement. Wang et al.[3] conducted a study which showed that preoperative customized exercise programmes are effective in improving the rate of recovery in the first 6 months after THR, and Unlu et al.[4] suggest that both home and supervised exercise programmes are effective 1 year after THR.

Traditional rehabilitation takes place in rehabilitation centres or hospitals; this requires patients to travel to appointments. An alternate rehabilitation method is using telerehabilitation technologies, where rehabilitation services are delivered into patients' homes, reducing time and financial costs.[5] Several studies have demonstrated that game-based virtual rehabilitation may provide a motivating setting for a wide variety of therapeutic goals[6] and lets therapists intervene effectively, especially for patients who have difficulty with transportation to rehabilitation centres.[7,8]

Microsoft Kinect® (Microsoft Corp., Redmond) is a tracking system that extracts information for 20 body joints. To be clinically useful, body motion devices must be simple to operate, reliable and have a high level of fault tolerance.[9] Kinect lets the users interact without any wearable devices on their body[10] and its use for telerehabilitation purposes is emerging in the literature. Pastor et al.[11] and Chang et al.[12] have studied the feasibility of Kinect oriented to upper limb rehabilitation. In both works, patients' results were superior after the sessions, and the

[1]Department of Languages and Information Systems, University of the Basque Country UPV/EHU, San Sebastian, Spain
[2]QEII Jubilee Hospital, Brisbane, Australia
[3]Division of Physiotherapy within the School of Health and Rehabilitation Sciences, University of Queensland, St. Lucia, Australia

Corresponding author:
David Antón, Department of Languages and Information Systems, University of the Basque Country UPV/EHU, Paseo Manuel de Lardizabal 1, Donostia-San Sebastian, 20018, Spain.
Email: david.anton@ehu.es

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system's acceptability by the patients was high. Su et al.[13] present a Kinect-based system to assist patients in conducting home-based rehabilitation. The system's evaluation matched that of the therapist in 80% of the cases, and users' usability and readability evaluation of the system was positive.

We developed Kinect Rehabilitation System (KiReS), a Kinect-based telerehabilitation system that places special emphasis on the provision, for physiotherapists and users, of a friendly and helpful interface. It allows the physiotherapists to define sets of exercises by recording themselves in front of the Kinect. The physiotherapists can thus define a variety of exercises applicable to many different health conditions. KiReS presents 3D avatars where the patients can observe their own avatar's movement while receiving feedback on their performance in comparison with the physiotherapist's avatar.[14] Users are monitored at the same time they are performing the exercises, and all captured data are recorded in the database to be accessed by the physiotherapist. The aim of this study was to validate KiReS for the provision of exercises for patients who have had a THR. A secondary aim was to evaluate the satisfaction of the users with the system.

Methods

Technical framework

From the technical point of view, three main features of the KiReS system are noteworthy for this application: (a) efficient real-time feedback; (b) good accuracy when recognizing exercises in real time; and (c) flexibility when adapting exercises to different physical pathologies.

The user interface provides the users with the graphical elements that guide them during a session. On the screen, patients can see two avatars (Figure 1). The avatar on the left acts as a guide, showing the movement the user has to do. The avatar on the right shows in real time the ongoing movement that the patient is performing. The interface also includes informative boxes at the bottom of the screen that indicate the next posture to perform and the number of exercises and repetitions left.

The information box in the middle of the bottom of the screen gives feedback about how well the patient is performing the current posture. This is done using text and colours indicating that the user has reached the posture and the precision of user's movement. In the upper centre of the screen there is a ribbon that changes as exercises are performed, and immediately under it a textual explanation of the exercise. During the session postures and movements are processed to produce a numerical rating of the performance. KiReS stores detailed raw data about the sessions that, if necessary, can be further analysed.

The therapy management tool allows the physiotherapist to define customized sets of exercises (that constitute the therapies) for the users by (a) using exercises already stored in a library, (b) combining those stored exercises, and/or (c) defining new customized exercises simply by recording themselves in front of the Kinect. A physiotherapist can freely tailor the session for an individual user, selecting the exercises and managing their parameters (hold time, number of sets and repetitions).

Participants

Participants were recruited from the Queen Elizabeth II Jubilee Hospital in Brisbane, Australia, during February–

Figure 1. User interface.

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March 2014. The inclusion criteria for the selection of the participants were: having undergone primary THR in last 4 months, full weight-bearing or weight-bearing as tolerated and normal mentation. The exclusion criteria were: revision THR, restricted weight-bearing post-operatively and having co-morbidities preventing participation in rehabilitation programme.

Patients had an average age of 56 (range 33–67 years), most of them (5 of 7) had hip replacement surgery in their left hip (Table 1).

Procedure

Patients were invited by their treating physiotherapist to participate in the study. Initially four sessions per patient were planned, each session of 30–45 min duration. Ethical clearance to conduct this study was provided by the relevant institutional review board, and all participants provide written informed consent prior to enrolment in the trial.

The use of KiReS involves the following steps: (1) the therapist defines the exercise session for the patient; (2) the patient performs the exercises with the system, and (3) the data obtained from the session is analysed and visualized.

A physiotherapist at QEII Hospital performed and recorded a total of 10 exercises for both the left and the right hip using the KiReS system. The physiotherapist also added a textual explanation for each exercise to be displayed on the interface during rehabilitation sessions.

Patients received 15 min of education prior to commencing their first session, outlining the objectives of the trial and also providing an explanation of how the system works. Patients were also reminded that at any moment they could stop if they felt pain or were too tired to continue. Participants performed exercises in front of the Kinect at a distance of approximately 2.5 m. A chair was provided on the side of their surgery to hold and lean on during the exercises if necessary. The tutorial included performing 2–3 repetitions of an exercise for patients to familiarize themselves with the system.

The exercise parameters for each patient were entered into the KiReS system by the treating physiotherapists. As sessions progressed these parameters were adjusted according to the clinical judgment of the physiotherapist, increasing or reducing the number of sets and repetitions when necessary.

Questionnaires

In order to assess patients' subjective perceptions we used a Likert scale questionnaire that patients completed at the end of each exercise session. The questionnaire consisted of 13 questions about the session with five possible answers from 1 (strongly disagree) to 5 (strongly agree). The questions were divided into three categories: the system; the experience of the user; and the interface. The questionnaire also asked about the participant's prior knowledge about telerehabilitation and asked for any suggestions regarding the system.

Table 1. Patients' characteristics.

	Age	Gender	Side	N° Sessions	Days post-op FS	Days post-op LS
1.	67	W	Right	4	28	45
2.	61	M	Left	4	108	124
3.	33	W	Right	1	59	59
4.	67	M	Left	4	3	24
5.	65	M	Left	3	7	20
6.	45	W	Left	2	10	18
7.	56	M	Left	1	2	2

FS: first session; LS: last session

Data analysis

Kinect raw data consists of a skeleton structure composed of 3D points that represent 20 body joints. During sessions, KiReS stores in the local database all the information regarding the exercises the patients performed, including the results they obtained and other performance measures. All data collected in this study were analysed descriptively. The following metrics (all of them include time stamps) were extracted from the raw data captured during exercises:

Joint position: The 3D coordinates of 20 body joints.
Posture evaluation: A rating value is obtained that represents the similarity between postures.
Resistance time: The actual hold time for the postures.
Movement evaluation: The limb angles changes during a movement.
Movement speed: Angular velocity of relevant limbs.
Exercise rating: Overall numerical rating of the accuracy of the exercises (the technical details of the recognition algorithm in KiReS were described previously[15]).

Results

During the trial, seven patients participated in a total of 19 sessions (Table 2). In these trials the system recorded a total of 3865 exercise executions (first column). From these exercises the system recognized 314 of them as incorrectly executed exercises (second column); in proportional terms, most of the errors centred around users 1 and 6 (Table 2). The KiReS system categorized 91.88% of the exercises performed by the patients as being correct. In Table 3 we present the correct performed exercises classified by exercise type.

Generally, there was an improvement in the accuracy of the exercises performed by participants over the course of the trial; those patients completing three or more sessions achieved significantly better results ($X^2 = 317.56$, df = 2, $p < 0.0001$).

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Table 2. Correct executions by patient.

	Total	Incorrect	% Correct
User 1	1320	184	86.06%
User 2	1285	48	96.26%
User 3	300	17	94.33%
User 4	288	12	95.83%
User 5	487	17	96.51%
User 6	141	35	75.18%
User 7	44	1	97.73%
	3865	314	91.88%

Table 3. Correct executions by exercise.

Exercise	Total	Incorrect	% Correct
Hip abduction right	260	14	94.62%
Hip flexion right	240	12	95.00%
Hip extension right	340	10	97.06%
Squat right	340	127	62.65%
Balancing right	440	38	91.36%
Hip abduction left	515	30	94.17%
Hip flexion left	339	21	93.81%
Hip extension left	451	20	95.57%
Squat left	441	33	92.52%
Balancing left	499	9	98.20%
	3865	314	91.88%

Figure 2 presents results from user questionnaires. In total 19 questionnaires were retrieved from participants. None of the users reported that they had heard about telerehabilitation or telemedicine before. Participants reported that the main negative features of the system were the size of the font and the structure of the interface, which some of them found distracting as they considered that some of the elements were not useful.

As a result of the feedback from the first four participants, an alternative user interface was designed during the trial. This interface featured simplified elements with larger fonts. The red avatar that showed the exercises was removed so the text description of the exercise becomes the main source of guidance along with the *semaphore* box. Also the size of all the elements was increased to make them more visible.

As the interface was adapted during the trial, the questionnaire results regarding the interface are split (see Figure 2); 13 questionnaires correspond to the original interface (white) and six questionnaires to the new interface (grey). The users were participative and five of them answered the open-ended question to propose ideas for improving the user experience.

Discussion

We made a full deployment of KiReS, defining step by step all the elements of a therapy in KiReS: postures, movements, exercises and the therapy itself. As previous studies have shown,[6–8] patients tend to show a general support for telerehabilitation and the possibilities for physiotherapy that systems like KiReS bring. Participants also found the interaction with Kinect easy and enjoyable, showing a predisposition to using the system again.

The analysis of the data collected during the sessions showed a high rate of correct executions (91.88%), even though none of the patient had used a system like this in the past. For those patients that completed at least three sessions, KiReS registered an increase in users' performance during the trials ($X^2 = 317.56$, df $= 2$, $p < 0.0001$). However, with just three or four sessions as reference, it is difficult to establish to what extent this is due to an improvement of the physical state of the participants and to the "learning" using the system.

The exercise performance results are quite uniform among patients but the results of User 1 and User 6 need to be highlighted (Table 2), as they showed a significantly lower rate. User 1 was the first user to test the system and we found that the system did not recognize the "Squat right" exercise well (Table 3). This exercise was poorly recorded; the postures for the start and end of the exercise were found to be too similar, leading to inaccurate recognition of the exercise. The exercise was fully re-recorded to solve the problem.

Anecdotally, we observed some limitation of the Kinect recognizing people of different shapes and with different clothing. User 6 was an obese user, and it was noted that in two of the sessions with this user the posture recognition was inaccurate. This low performance was due to Kinect recognition errors and not to actual wrong executions on the part of the patient.

A limitation of KiReS is that recognition is not accurate if an element that was not present during the recording is introduced in the image. Nevertheless, when the exercises or the patients require an extra element (e.g. a chair for support), it can be included as long as this element was also present during the recording phase. We would therefore recommend that a set of guidelines covering these factors be developed prior to wider-scale uptake of Kinect technology. Moreover, this trial highlighted that Kinect performs better in an uncluttered environment, which has implications for the deployment of the technology into a patient's home where space and furnishing cannot be controlled for.

With respect to the post-session questionnaires, we had positive feedback from the patients regarding the system, although some constructive criticism, especially about the interface, was received. The levels of acceptance and usability we found were consistent with those obtained in previous research about virtual therapy and telerehabilitation.[6,16,17] The overall satisfaction with the experience of using KiReS was positive (Q4: 4.67). The participants in the trial were all familiar with doing their exercises at home and could appreciate the advantages of KiReS for facilitating their exercise routine. Patients also considered

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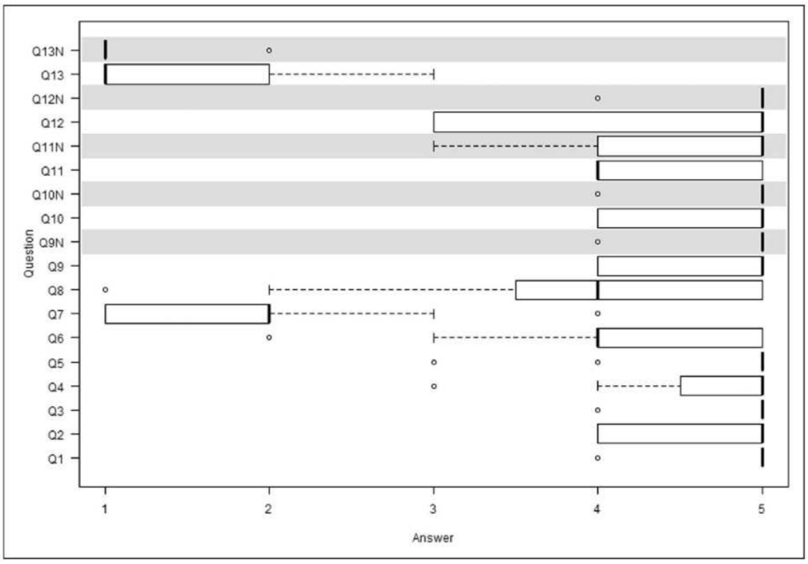

Figure 2. Questionnaire results (median & IQR) [As questions 7 and 13 are negative, lower values are better]

exercising with KiReS as good as regular sessions, and reported that it was a helpful tool for doing their exercises at home (Q3: 4.75 and Q2: 4.63). The results also reveal a high level of interest (Q5: 4.86) in the participants' ongoing use of the system. Previous trials have shown this motivation on keep using similar systems for physical rehabilitation.[11,12] When the satisfaction results are considered according to the three themes (system, personal experience and interface), a mean score of 4.71 for the system and 4.4 for the personal experience category was seen. We found that the evaluation of those patients who tested the system with the new interface was higher (4.77) than with the original interface (4.43), and this was significantly different ($X^2 = 6.6347$, $df = 2$, $p = 0.03625$). This is an expected result as we followed a user-centred interface design paradigm[18] and improvements in the new interface were based in the opinions of these very patients.

There are some limitations in the present study. First, the number of participants (seven) was small, so they might not represent faithfully a THR population. Second, the patients presented different time post-surgery from days to months, so results might show bias because of this factor. Third, although KiReS was tested following the same procedure as if it were a telerehabilitation session, it was tested locally. Lastly, only three of the patients participated in the originally programmed four sessions, so this limited the data collected. Therefore, our results may not generalize to wider groups of patients, but as a preliminary trial we consider them encouraging for further research on this area. A system like KiReS has shown to be a valuable tool for telerehabilitation; future research will integrate KiReS with the new version of Kinect, and further validation studies are planned to take place.

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Conflict of interest

None declared. 1

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D. Knowledge-based Telerehabilitation Monitoring

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Knowledge-based Telerehabilitation Monitoring

D. ANTÓN, UNIVERSITY OF THE BASQUE COUNTRY UPV/EHU

I. BERGES, UNIVERSITY OF THE BASQUE COUNTRY UPV/EHU

J. BERMÚDEZ, UNIVERSITY OF THE BASQUE COUNTRY UPV/EHU

A. GOÑI, UNIVERSITY OF THE BASQUE COUNTRY UPV/EHU

A. ILLARRAMENDI, UNIVERSITY OF THE BASQUE COUNTRY UPV/EHU

Abstract. In this paper we describe the main features of an innovative home telerehabilitation system that offers, for both users and physiotherapists, actionable information to gain new insight in the telerehabilitation processes. From the point of view of users, it offers a friendly and immersive exercise interface that shows in two 3D avatars how an exercise must be executed and how the user is executing it respectively. Moreover, during a therapy session, informative elements show up-to-date information to guide and encourage the user. From the point of view of the physiotherapists, the system suggests them appropriate exercises that can be used to define customizable telerehabilitation therapies. Furthermore, another novel contribution of the system is its capacity to transform the raw data collected from a user into information that can help the physiotherapist to improve therapy decision making or the redefinition of existing therapies.

Keywords: Telerehabilitation, Telemedicine, Knowledge representation, Ontology, Kinect.

1 Introduction

People's higher survival to diseases and traumas which leave physical sequels has generated an increase in demand for rehabilitation processes. Rehabilitation is a critical component for resuming normal activities of daily living. For example, Maire et al. [1] indicate that the improvement in physical fitness and functional status as a result of rehabilitation is associated with better health status after hip replacement.
Traditional rehabilitation takes place in rehabilitation centers or hospitals which many times get saturated and which requires patients to travel to appointments. This travel is often associated with both time and financial costs [2]. An alternate rehabilitation method is using telerehabilitation technologies where rehabilitation services are delivered directly into patients' home [3], reducing so the congestions of the centers and letting physiotherapists intervene effectively especially for those patients who have difficulty with transportation to rehabilitation centers [4].

adfa, p. 1, 2011.

A common component in recent telerehabilitation systems is motion capture technology [5], [6]. The use of telerehabilitation systems with motion capture has been shown to increase the intensity of rehabilitation and enhance user experience [7], [8]. Another consideration to attract users' attention and interest in the system is the incorporation of avatars. According to Ortiz et al. [9] there are many potential advantages in the use of avatars, rather than other conventional methods.
In this paper we show KiReS, a telerehabilitation system that makes use of Kinect's technology to analyze patients' exercises through the monitoring of the position of the body in space. Microsoft Kinect® (Microsoft Corp., Redmond) is a markerless camera based visual tracking system that extracts information about the three dimensional position of 20 different body joints. Developed primarily for gaming purposes, the device lets the users interact without carrying any wearable devices on their body [10], [11]. Currently, telerehabilitation systems can be found both in an academic setting as in a commercial environment. However, KiReS provides some novel features that we summarize in the following:

- **Friendly and helpful interaction with the system**. This means that KiReS combines the use of a non-wearable motion control device with motivational interfaces based on avatars, since successful rehabilitation depends largely on the user's motivation and compliance with therapy. Furthermore, KiReS facilitates physiotherapists an interface that is based on the therapy protocols they typically use with the added value that it provides an easy way to define new exercises.
- **Provision of actionable information.** KiReS uses different techniques to provide actionable information. On the one hand, it manages a novel domain specific ontology that we have built, that supports physiotherapists in the therapy design process by: assuring the maintenance of appropriate constraints and selecting for them a set of exercises that are recommended for the user. This type of information is not provided by current systems and it has been recognized as very interesting by the consulted physiotherapists. On the other hand, it is able to convert low-level recorded Kinect data into high-level knowledge.
- **Monitoring of rehabilitation sessions**. KiReS incorporates an algorithm that evaluates online performed exercises and sets if they have been properly executed by comparing the obtained results with the recorded reference data. Automatic exercise evaluation is a key feature of our proposal, taking into account that, in home oriented telerehabilitation systems, it is crucial that the user is autonomously evaluated without the direct intervention of the physiotherapist during rehabilitation sessions.

The rest of the paper is organized as follows: In section 2 we introduce some related works. Next, in section 3 we briefly introduce the KiReS workflow. Then, in sections 4 and 5 we address the therapy planning and the therapy execution and controlling processes, respectively. Finally in section 6 we present some conclusions.

2 Related Works

Existing home telerehabilitation systems make use of different types of interaction devices and are oriented to the treatment of many physical pathologies. In a first approximation we can classify them into two main groups. In the first group those works that propose to wear devices are included. Among them we can mention ArmAssist [12]. The proposed system evaluates online performed arm exercises by using a low-cost device and a table mat that communicates with a PC. The second group includes those systems that advocate that users do not wear devices but they only use them. In [13] Lockery et al. present a system that uses a webcam and adaptive gaming for tracking finger-hand movement. They attached trackers to some objects and a webcam captures user's hand and generates some metrics that provide information about the quality, efficiency, and skill of the user. More recently, in the context of hand evaluation, Iosa et al. [14] present a Leap Motion based rehabilitation system for elderly people that have suffered subacute stroke. This pilot study uses Leap Motion for conducting a videogame-based therapy that evaluates hand's ability and grasp force. However, a great number of works advocate for using *Kinect*, a motion capture device that tracks user full body movements without physical contact. In this line, Gotsis et al. [15] present 21 game concept prototypes which receive and process data sent by Kinect, but the evaluation model is not dealt with by the authors. Pastor et al. [16] and Chang et al. [17] have studied the feasibility of Kinect oriented to upper limb rehabilitation. In both works patients improved their motion ranges and systems acceptability was high. Su et al. [18] present a system to assist patients in conducting home-based rehabilitation. System's evaluation matched that of the therapist in 80% of the cases, and users' usability and readability evaluation of the system was positive. Gabel et al. [19] developed a method focused on full body gait analysis using Kinect. Results showed accurate and robust gait analysis using Kinect and its viability for diagnosis and monitoring of treatments in domestic environments. Galna et al. [20] developed a game aimed at training dynamic postural control for people with Parkinson Disease. Finally, some proposals which are commercial products such as [21], [22], [23] can be found but they do not show many technical details concerning their internal behavior and are oriented to specific pathologies.

In our case, we have paid special attention in developing motivational interfaces and providing an accurate online evaluation of exercises. Although these features are also considered somehow in some of the previous works, we have not found any that additionally provides the type of actionable information that KiReS provides.

3 KiReS workflow

The use of KiReS involves the performing of the activities shown in the UML activity diagram of Fig. 1, which are executed by three different actors: the physiotherapists, the users and the knowledge manager of the system. Some of these activities correspond to the therapy planning (purple) and others to the therapy execution and controlling (green).

With respect to the therapy planning, first of all, the physiotherapist makes an initial evaluation of the user, which includes what it is known as anamnesis. As a result of this evaluation some knowledge about the user is asserted in the Telerehabilitation Ontology (*TrhOnt*). After that, the physiotherapist assigns appropriate exercises to the user taking into account those recommended by *TrhOnt* (the ontology includes exercise descriptions and the exact details of all joints and movements involved in the

exercises are stored in the *KiReSdb* database). If the physiotherapist wants to assign a particular exercise that does not exist yet, then the physiotherapist can create it by using the "Create New Exercise" activity.
Concerning the therapy execution and controlling process, once the exercises have been assigned, the user can perform them by using KiReS. Those exercises are monitored and the results are stored in *KiReSdb*. After the exercises have been performed and monitored two different activities can take place: 1) the physiotherapist can make a user reevaluation in order to finish the rehabilitation process or to assign new exercises to the user; and 2) a knowledge extraction process is performed in order to find new knowledge to add to the ontology.

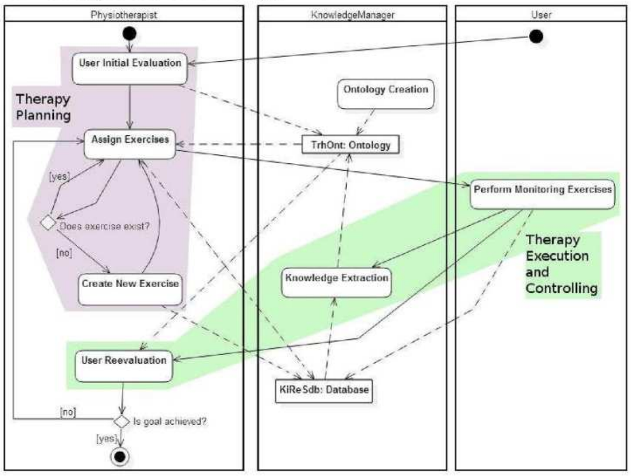


Fig. 1. KiReS activity diagram

4 Therapy planning

One core artifact for the KiReS system is the telerehabilitation service ontology *TrhOnt*. It supports therapy planning by representing different kinds of knowledge and by providing some inference services. Creation of new exercises is also a part of the therapy planning process. KiReS offers an interface that provides assistance to define exercises and the *TrhOnt* guarantees coherent definitions.

4.1 The telerehabilitation ontology (*TrhOnt*)

TrhOnt is an OWL ontology composed of four interrelated parts of knowledge. We have designed it as a service artifact; therefore, OWL reasoners' capabilities play a crucial role. In the following we explain more about each type of knowledge.

- *Patient knowledge:* This part consists of classes and properties for representing information such as personal and family data, goals, symptoms, results of physical examination, diagnoses, reported value in the Visual Analogue Scale (VAS) [24] and everything captured at the anamnesis.
- *Anatomy knowledge:* The Foundational Model of Anatomy[1] (FMA) is a domain ontology that represents a coherent body of explicit declarative knowledge about human anatomy. We have extracted a module from FMA-OWL [25] that is useful for the desired telerehabilitation process based on Kinect. FMA-OWL in its version 4.0 contains more than 100000 classes, 156 object properties connecting the classes, and more than 700000 axioms.
- *Movements and exercises knowledge*: Classes and properties have been defined to represent atomic movement and complex movement (i.e. those compose of atomic). Basically, a movement is characterized by its type, its associated joint and its amplitude (min and max range of movement). Furthermore exercise classes are defined as compositions of movements.
- *Experts' domain knowledge: TrhOnt* includes axioms that reflect specific knowledge about characteristics of recommended (and contraindicated) exercises depending on patient's state. This knowledge will be useful to the therapist during the "Assign Exercises" activity. Due to the information recorded in the Patient knowledge part, inference services (such as class subsumption and instance realization) applied on expert's domain knowledge are able to offer a list of recommended exercises for that patient.

The *TrhOnt* ontology takes part in the activities that evaluate and reevaluate users, the activity that assigns exercises to users and in the knowledge extraction activity. The ontology has been implemented using Protégé [26]. In Fig. 2 we show a snapshot of the class `GlenohumeralJoint`.

[1] http://sig.biostr.washington.edu/projects/fm/FME/index.html

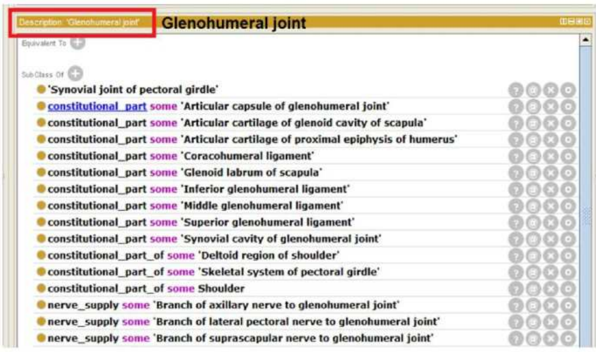


Fig. 2. Axioms about Glenohumeral Joint in Protégé

4.2 Creation of new exercises

KiReS offers an interface for the physiotherapist that provides assistance to create exercises step by step, this way it is guaranteed that the exercise structure is respected and our recognition algorithm is able to evaluate them.

A posture is the simplest element of an exercise and therefore necessary for the definition of any other structure. The physiotherapist performs the posture in front of the system and records it (see Fig. 3). Then, a recording player tool allows the physiotherapist to select frame by frame which postures to store from the recording. Before storing postures, the posture recognition algorithm analyzes them in order to guarantee that they are similar enough. This type of similarity verification avoids adding very different postures with the same name and, at the same time, with well labeled postures the accuracy of the recognition algorithm is higher.

Movements have a name associated to identify them and are defined with two postures (initial and final) and with the recording of the transition between those postures (Fig. 4). Once both postures are selected, the system analyzes them. The relevant joints that best represent the transition from initial posture to final posture are selected and these joints are recorded and stored. Movement recording makes use of the same features as posture recording. The physiotherapist selects the movement to record and visualizes the initial and final postures of the movement. The posture recognition algorithm checks when the therapist makes both the initial and final posture and in the meantime the trajectories of the relevant joints are recorded. After reaching the final posture the recording player tool shows the movement and the therapist can replay it and decide whether to store it in the KiReS database or to repeat the recording. The information concerning the name, the initial and final postures, the type, the joint of the movement and the range of motion involved is added to the ontology to allow reasoning over movements.

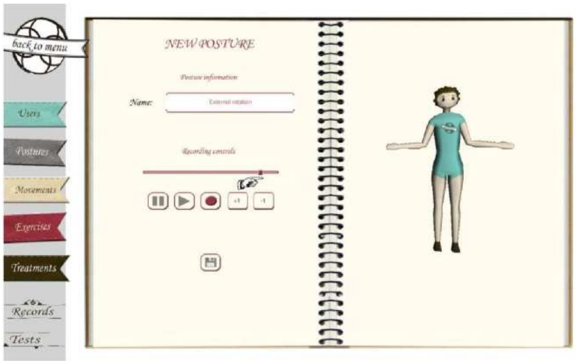


Fig. 3. Posture edition

Lastly, exercises are defined by assigning movements to them. Simple exercises can consist of just one atomic movement but complex exercises are a combination of atomic movements, which create a sequence of movements. The only restriction when combining movements is that the final posture of a movement must match the initial posture of the next one. The exercise creation interface allows the therapist to define the composition of an exercise. It shows a form to fulfill data about the exercise and two lists with the movements assigned to that exercise and with the available movements to add. Once this is done the exercise will be stored in the system (in the database and also in the ontology for reasoning) and will be available to be added to a therapy session.

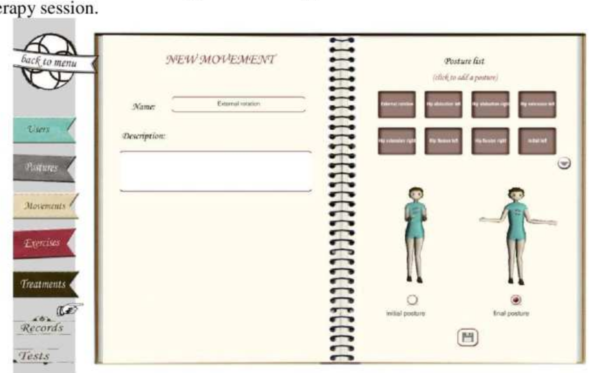


Fig. 4. Movement definition

For the implementation of the interfaces Unity 4 [27] was used and all the scripts that control the behavior of the interface were developed in C#. The avatars and the rest of the 3D models were modeled in 3Ds Max and exported to Unity. However, official Kinect drivers are not directly compatible with Unity, for this reason, some open source C# scripts [28] were used for interaction. This library provides basic functionality for Kinect for Windows in Unity.

5 Therapy execution and controlling

Users are monitored at the same time they are performing the exercises and all captured data are recorded in the *KiReSdb*. After that the physiotherapist can make a user reevaluation in order to finish the rehabilitation process or to assign new exercises to the user. Moreover, the knowledge extraction activity is performed in order to find new knowledge to add to the *TrhOnt* ontology.

5.1 Performing exercises

When users are performing exercises at home the interface must meet two requirements. It has to be easy to understand and at the same time attractive enough to encourage users to participate in therapy. The exercise interface of KiReS presents two 3D avatars that guide the user (see Fig. 5). The avatar on the right shows the movements of the user in real time, while the avatar on the left acts as a instructor, showing the exercise the user has to do.

The four boxes below (see Fig. 5) provide information about the ongoing therapy session to the user. The two boxes on the right show the number of series and repetitions left[2]. When the user has done all the series the session is finished. The box on the left shows the name of the next posture the user has to reach. The box in the middle shows the "state" of the current movement, it is continuously updated by the exercise recognition algorithm and it displays information to guide the user in real time. Besides, when the user is close to reaching a posture, the box indicates with a three level color scale (red, yellow and green) how close s/he is from reaching the posture. In the upper center of the screen there is a ribbon that shows the exercise as a list of postures that have to be reached in the current execution. This ribbon is updated as the user completes exercises. Under this ribbon a textual explanation of the exercise is displayed. When a session is finished a new screen shows the results of the session: the execution accuracy of all exercises execution, the time taken to finish the session and the final evaluation of the session.

In summary, the avatars and the informative boxes provide information to the user. This way, the system empowers and keeps the user aware of his/her therapy, but also provides a game-like immersive experience that motivates and makes the therapy more enjoyable.

[2] A series is the list of exercises to be done on a session and the repetitions is the number of times an exercise has to be done in each series.

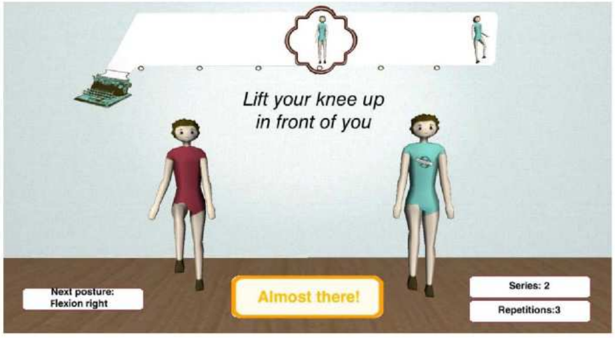


Fig. 5. User exercise interface

5.2 Exercise Monitoring

While the user is performing the exercises, the system evaluates them and sets if they have been properly executed by comparing the results obtained with the recorded reference data.

As mentioned in section 4, exercises usually consist of series of movements. Each movement is composed of an initial posture, a final posture and the angular trajectories of the joints involved in the movement (the relevant joints). Both the initial posture and the final posture of a movement are identified.

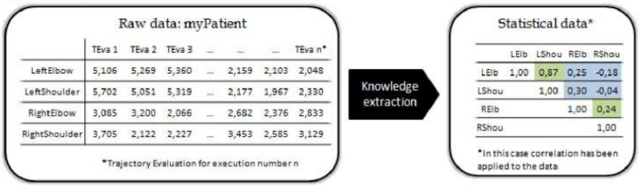
- *Identification of the initial posture:* When starting a movement the system waits for the user to get into the initial posture. The posture classification method checks the user's current posture until it identifies it as the initial one. These checks are performed in real-time at a rate of about 30 checks per second, which is the frequency with which Kinect provides data. When the initial posture is identified the system starts the trajectory recognition.
- *Trajectory recognition:* The trajectory recognition method has as a main purpose to recognize if the movement itself is well performed. During the recognition, the trajectory of each relevant joint involved in the movement is compared to the trajectory of the same joint recorded as reference for that movement and a distance is calculated between those two trajectories. If the distance is less than a threshold value the trajectory path is considered to be correct, and incorrect in opposite case. In order to calculate the distances among trajectories, we use a variant of the Dynamic Time Warping (DTW) algorithm [29].
- *Identification of the final posture:* While analyzing the trajectories, the exercise recognition method also checks the posture of the user. When the final posture is identified the movement is finished. If an exercise has more movements the method tries to identify the initial posture of the next movement. Identifying the final posture of a movement has a peculiarity given the context of rehabilitation. In

some stages of therapy what is expected from the user is to try to reach that position or to at least make the physical effort to reach it. Thus, the method adapts the threshold depending on the time spent performing the movement. The threshold is multiplied by a flexibility factor that makes the algorithm be less rigid in posture classification. Finally, the overall exercise rating is the average of the rates of all the movements that compose the exercise. Detailed information of the algorithm can be found in [30].

As said before, the flexibility factor is a very important concept in the evaluation of exercises. Several implementations of the exercise monitoring algorithm have been analyzed in order to adapt an adequate strategy. That strategy has been selected and validated, as statically significant, by applying Friedman and Nemenyi tests.

5.3 Knowledge Extraction

The data obtained during exercise execution and evaluation that are stored in the database of KiReS can be analyzed to extract knowledge in order to provide more information to the physiotherapists. This new knowledge is added to the ontology and will be available to the physiotherapist in the activities "Assign New Exercises" and "User Reevaluation".
For example, a statistical analysis of raw data obtained from the telerehabilitation session of a user can find relevant information for the therapist. In Fig. 6 we show a shoulder exercise execution with a symmetric movement in which both arms are moved at the same time. The user raises up both arms to the head and then moves them down. The raw data analyzed consists on the results of evaluating the trajectories of several body joints during a session. A statistical analysis allows obtaining the correlation among these data that can be of interest for the physiotherapist. The conclusion is that "The left arm is progressing, both elbow and shoulder are recovering, but the recovery of the right arm might not be uniform and the patient may need a check". New assertions will be added to the ontology that will be used to notify the physiotherapist.



	TEva 1	TEva 2	TEva 3	...	...	...	TEva n*
LeftElbow	5,106	5,269	5,360	...	2,159	2,103	2,048
LeftShoulder	5,702	5,051	5,319	...	2,177	1,967	2,330
RightElbow	3,085	3,200	2,066	...	2,682	2,376	2,833
RightShoulder	3,705	2,122	2,227	...	3,453	2,585	3,129

*Trajectory Evaluation for execution number n

	LElb	LShou	RElb	RShou
LElb	1,00	0,87	0,25	-0,18
LShou		1,00	0,30	-0,04
RElb			1,00	0,24
RShou				1,00

*In this case correlation has been applied to the data

Fig. 6. Knowledge extraction example

5.4 User Reevaluation

After the user has performed the exercises and the knowledge extraction process has been made, the physiotherapist must decide if the user has achieved the rehabilitation goals, or if new exercises must be assigned to the user. For that, the new extracted knowledge about user's medical condition (obtained ROM, accuracy, speed…) will be available in the ontology ready to be checked by the physiotherapist.

6 Conclusions

KiReS provides home-based telerehabilitation with a natural form of interaction. The interface for the users includes two avatars, one with which the user can see the exercise s/he must do and another one with which s/he can see how s/he is actually doing it. From the point of view of physiotherapists, KiReS allows them to define customized therapies for the users. Moreover, physiotherapists can also analyze the knowledge extracted from the data recorded from the users' executions in order to track the users' evolution, obtain new knowledge about exercise performance or use the data to identify and correct undesired situations. Another relevant aspect to highlight is that KiReS is not designed for a specific pathology; the system can be loaded with a broad spectrum of exercises as opposed to the majority of proposals that consider fixed exercises to specific physical pathologies.

KiReS was tested in a trial we performed in a rehabilitation center. Moreover, for this trial we prepared questionnaire that all the users agreed to fill at the end of the session. This early trial results showed some aspects that we consider relevant about the users' interaction and experience with the system. First, we found that the interaction with Kinect was easy to learn for the users and they found the system comfortable to interact with. Second, they see the system as a complement to their therapy that can improve medical attention but not as effective as the ordinary session. Third, they showed a predisposition to using the system again and felt satisfied with the experience. Finally, the overall impression of the interface content was positive and users found the information 3D avatars gave to them helpful.

As future work we are considering the possibility of enhancing the information KiReS retrieves by adding biosignal tracking devices such as pulse oximeters. This would require updating *ThrOnt* to incorporate these new relevant data. Also in the future we expect to adapt the system to work with the new version of Kinect.

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E. Real-time communication for Kinect-based telerehabilitation

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- Authors: David Antón, Gregorij Kurillo, Alfredo Goñi, Arantza Illarramendi and Ruzena Bajscy
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Real-time communication for Kinect-based tele-rehabilitation

David Anton, Gregorij Kurillo, Alfredo Goñi, Arantza Illarramendi and Ruzena Bajscy

***Abstract*—As chronic diseases and the demographic changes alter the trends in the population, more pressure is put on achieving an efficient health management. The use of the evolving telecommunications industry combined with medical information technology has been proposed as a solution to reduce health management and to provide remote medical services through the Internet and mobile devices. This is why telerehabilitation systems are being developed, to allow monitoring and support of physiotherapy sessions at home. In this scenario the use of Kinect, a non intrusive tracking device with a reasonable cost, is gaining popularity. Moreover, a requirement that is also being imposed is to facilitate real-time video and audio transmission. In this paper KinectRTC is presented, an innovative tele-rehabilitation approach that allows for stable real-time transmission video, audio, depth, and skeleton data provided by Kinect. In KinectRTC video and audio streams are managed based on the state of the network and the available bandwidth so their quality is adapted to guarantee the real-time performance of the communication.**

***Index Terms*— WebRTC, Kinect, Telerehabilitation, Real-Time Communication, eHealth.**

I. Introduction

THE use of Health Information Technology (HIT) has been promoted as having tremendous promise in improving the efficiency, cost-effectiveness, quality, and safety of medical care delivery [1, 2]. Various telemedicine programs and technologies have been proposed to improve health management, reduce hospital re-admissions and the overall cost of care, and to reduce burden of travel for patients. This travel is often associated with both time and financial costs [3]. Another advantage of these programs is an easy access by the health-care professionals to the data collected from users via the Internet and mobile devices [4, 5].

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David Anton, Alfredo Goñi and Arantza Illarramendi are with the Department of Languages and Information Systems, University of the Basque Country UPV/EHU, Donostia-San Sebastian 20018, Spain e-mails: (david.anton, alfredo, a.illarramendi) @ ehu.es.

Gregorij Kurillo and Ruzena Bajcsy are with Department of Electrical Engineering and Computer Sciences, University of California at Berkeley, Berkeley CA 94720, USA e-mails: (gregorij, bajcsy) @ eecs.berkeley.edu

Telemedicine programs also provide specialized healthcare services to populations living in rural areas using remote monitoring technologies and video-conferencing. This approach to medical care delivery has been expanding for several years and currently covers various specialty areas, such as prenatal care, cardiology, rehabilitation, stroke and others. Until now the primary areas of video-based telemedicine have been in (a) simulation and training, (b) video-consultation and remote diagnosis, and (c) video-monitoring and vital signs tracking. In the past, majority of the telemedicine systems have used dedicated networks for transmission of data. However, recently several cost-effective commercial products have emerged that support secure real-time video connection between a health provider and a patient (e.g., Vidyo, VSee). Although such video monitoring has been quite successful for some specialty areas the remote physical therapy has been by and large lagging behind due to various reasons that among others include the cost of video equipment, insurance reimbursement model, and difficulty of obtaining reliable observations only from video while providing effective feedback to the patient remotely. Nevertheless, it is contrasted that tele-rehabilitation systems can provide an interesting alternative to traditional rehabilitation by delivering the service directly into patient's home and data collected via sensors during sessions can be further processed to provide more effective health interventions [6-8].

Various forms of tele-rehabilitation are experiencing a rapid growth and are thus, becoming a significant segment of telemedicine and e-health. The distance barriers can be overcome by applying various forms of telecommunication, including voice, video, and virtual reality [9]. Research works have demonstrated that virtual reality (VR) game-based rehabilitation may be enjoyable and engaging [10] and provide a motivating setting for a wide variety of therapeutic goals [11, 12].

Concerning video transmission the majority of the tele-health systems have relied on single video transmission [13, 14] which in case of physical therapy provides partial information on patient's performance and hinders obtaining reliable observations (i.e., measurements) while providing effective feedback to the patient. Multi-view video or 3D video (RGB + depth) can on the other hand deliver additional information that can assist the physiotherapist in evaluating correctness of patient's movements. When transmitting video, the network bandwidth is one of the major limitations in such applications. The use of standard RGB video compression techniques can significantly reduce the size of video transmission; however efficient compression and transmission of 3D depth data is still an open problem [15]. A real-time video/depth/audio transmission is essential to achieve a convenient and effective telerehabilitation session and positive user experience. Physiotherapist should be able to demonstrate exercises remotely to the patient while also being able to observe patient's performance. And the patients should be able to communicate to the physiotherapist any question or concern about their performance. Avoiding cuts and delays in the data streaming and guaranteeing the stability of the communication are still research challenges in transmission of 3D video.

To alleviate some of the issues in multimedia communication between various platforms and across different network configurations, an open source Real-Time Communications (RTC) framework, WebRTC, has been proposed [16, 17]. WebRTC is a collection of standards, protocols, and APIs, which enables peer-to-peer audio, video, and data sharing in real time. Due to its implementation of secure communication protocols and platform independency, it is an ideal network framework for real-time interaction in remote physical therapy.

Concurrently, the recent advances in sensor technologies such as release of Microsoft Kinect camera [18] have facilitated cost-effective and relatively accurate acquisition of human movement [19-21]. The Kinect camera has been to date applied in several applications aimed at physical rehabilitation [22-26]. The combination of an open source real-time networking framework, such as WebRTC, and the Kinect camera can provide the next step in remote physical therapy.

This paper presents the main features of developed KinectRTC framework, based on WebRTC and Kinect, that allows for real-time interaction between a physiotherapist and a patient inside a virtual environment, while providing quantitative information on patient's movement. KinectRTC facilitates stable and secure transmission of video, audio and Kinect data (i.e., camera parameters, skeleton data, and depth image) in real-time between two peers. The remote peers can communicate to each other using 3D video and audio while the motion data captured by the Kinect are streamed for real-time feedback or stored for later analysis. This complementary functionality to video-conferencing systems was envisioned to allow for remote real-time interactive rehabilitation sessions. KinectRTC has been integrated in two existing research telerehabilitation platforms such as Tele-MFAST [15] or KiReS [27] in order to demonstrate its applicability in two different scenarios.

The reminder of this paper is organized as follows, in Section 2 WebRTC technology is presented and in Section 3 the structure and implementation of KinectRTC is described and its use in two experimental scenarios. Section 4 shows the performance results obtained and finally Section 5 presents some conclusions and future work.

II. WebRTC

Web Real-Time Communication (WebRTC) is a collection of standards, protocols, and APIs, the combination of which enables peer-to-peer audio, video, and data sharing between peers in real-time [16, 28]. WebRTC has two different layers, WebRTC C++ API for browser developers or native RTC applications developers and a Web API for Web Application developers [17]. To acquire and communicate streaming data, WebRTC implements the following APIs:

PeerConnection API (sending and receiving media) allows the direct communication between users (P2P). To open a connection and have a signaling negotiation, it requires to first establish a signaling channel. To allow media streams to cross through Network Address Translation (NAT) and firewalls, the API uses the Interactive Connectivity Establishment (ICE) Protocol with Session Traversal Utilities for NAT (STUN) and Traversal Using Relays around NAT (TURN).

MediaStream API (camera and microphone access) is an abstract representation of an audio and video data stream. Two types of streams are available: Local MediaStream and Remote MediaStream. Local MediaStream is a captured stream on the same system (camera and microphone) and Remote MediaStream is a stream that is received from the remote peer. This stream can be used to show, save and send its content from peer to peer.

DataChannel API (sending non-media data directly between peers) is a bidirectional data stream for peer-to-peer transmission. It allows transfer of any data resorting to another set of protocols such as Stream Control Transmission Protocol (SCTP) encapsulated in Datagram Transport Layer Security (DTLS). Data transmitted via DataChannel can be either UTF-8-encoded application data (ASCII) or binary data. Use of SCTP facilitates a solution for NAT with security, source authentication and data integrity, for the data requiring transmission.

WebRTC incorporates on one hand a fully featured audio and video engines that take care of encoding and decoding with all the signal processing, such as echo cancellation, noise reduction or image enhancement (see Figure 1); and on the other hand, data channels that work as a generic transportation service allowing to exchange generic data in a bidirectional peer to peer fashion.

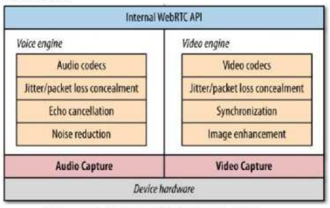

Figure 1: WebRTC internal API

A. Audio and Video Engines

Enabling a rich teleconferencing experience requires an application to be able to access the system hardware to capture both audio and video. However, raw audio and video streams are not adequate on their own since each stream must be: processed to enhance quality, synchronized with other streams, and the output bit-rate must be adjusted to the continuously fluctuating bandwidth and latency between the clients.

The video engine performs similar process by optimizing image quality, applying compression and codec settings and processing data with the jitter and packet-loss concealment algorithm. Similarly, the audio stream acquired from a device must be processed for noise reduction and echo cancellation and subsequently encoded with one of the audio codecs compatible with WebRTC. Finally, before sending data, a jitter and packet loss concealment algorithm is applied. On the receiving end, this process is reversed, and the client application must decode the streams in real-time and be able to adjust to network jitter and latency delays [29].

B. Data Channels

Data channels are designed to transfer arbitrary data directly from one peer to another. They work with the PeerConnection API, which enables peer-to-peer connectivity. The transport properties of a data channel, such as order delivery settings and reliability mode, are options configurable by the peer as the channel is created. As encryption is mandatory for all WebRTC components, data channels are secured with Datagram Transport Layer Security (DTLS). DTLS is a derivative of Secure Sockets Layer (SSL), meaning that data will be as secure as using any standard SSL based connection [29, 30].

III. KinectRTC

KinectRTC extends WebRTC to stream 3D video (RGB+depth), audio and skeleton data retrieved from Kinect. The process requires connection initialization via a server where clients connect to enlist the peers (see Figure 2). The signaling process begins with the registration of a peer on the server. When a client is connected to the server it receives the list of the available peers. Next, a client selects one of the peers and the connection is negotiated with the remote peer. In order for the WebRTC application to establish a direct connection, the clients exchange information to coordinate communication through a signaling process Peers negotiate the following properties to establish a connection:

- Session control messages used to open or close communication and error messages.
- Media metadata such as codecs and codec settings, bandwidth and media types.
- Key data to establish secure connections.
- Network data, such as a host's IP address and port as seen by the outside world.

The key information that needs to be exchanged is the multimedia session description, which specifies the necessary transport and media configuration necessary to establish the media plane.

It is worth noting that the WebRTC standards allow for any codec to be negotiated if the application implementation supports it. The WebRTC media plane is designed to avoid, as far as possible, the need to relay media streams to intermediaries. WebRTC media plane also incorporates an exchange of information on the quality of the network. This creates more intricate options for adapting the media coding to best-effort network conditions [16].

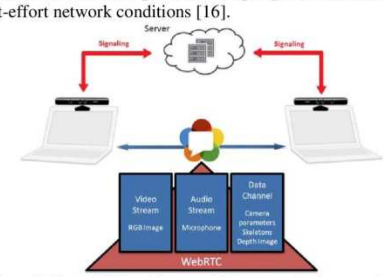

Figure 2: KinectRTC architecture, P2P connection is opened after receiving a list of available peers from the server

Once the connection between peers is established they start streaming data. In this case, KinectRTC uses the two kinds of streams that WebRTC provides; video/audio and the data channel. In the case of multimedia streams, WebRTC can be configured to manage these streams and adapt the quality of the RGB image and the audio to the available bandwidth. This means that if necessary the video resolution and the audio bit rate are automatically reduced to improve data transfer. On the other hand, default data channels do not include yet any function to adapt transmission to the available bandwidth beyond options to set reliable/unreliable mode or the retransmission of packets parameters.

A. Server application

WebRTC offers P2P communication but it still requires a server to keep track of the peers and to establish the initial connection. Peers are registered in the server, allowing the server to provide a list of available peers. After a request for connection is received and connection is established via P2P protocol, the server does not have any role in the data interchange between the peers.

B. Client application

The client library was implemented in C++ using the Native C++ API of WebRTC. This implementation consisted of the PeerConnection configuration for video/audio and data transmission gathered from the Kinect. The system was developed as a Windows application. The KinectRTC client provides the following functionality:

- Definition of the server to connect
- Peer selection and connection/disconnection
- Selection of data to send (audio, video, depth, skeletons)

1) *Audio, video and data*

When the P2P connection is established the KinectRTC clients start streaming video, audio and binary data. Since the Kinect audio drivers provide Windows OS with access to its microphones, the Kinect audio source is directly assigned to the audio stream.

On the other hand, Kinect camera is not recognized as a video source by the Windows OS. The access to the Kinect video stream was thus obtained via Microsoft Kinect SDK. For this purpose a customized device class was created to feed the WebRTC video stream with RGB video frames from Kinect. The video from Kinect is captured at the rate of 30 frames per second (FPS) and passed on to WebRTC video device class with the same frame rate.

The remaining Kinect data, such as depth map, camera parameters (e.g., focal length, camera orientation), and the skeletons is transmitted through a WebRTC data channel that concentrates all the binary data. KinectRTC uses Protocol Buffers library [31] to encode camera parameters and skeletons as both have a fixed structure. The Protocol Buffers library allows for fast and automatic encoding/decoding of C++ objects into binary buffers that can be sent/received over the network. To further reduce the size of transmitted data, the depth map frames are also compressed using lossless compression via z-lib [32].

C. *KinectRTC Prototype Platforms*

1) *Tele-MFAst*

KinectRTC was integrated in the original Tele-MFAsT [15] framework developed at UC Berkeley in order to verify its operation. Tele-MFAsT is a telerehabilitation system designed for remote motion and function assessment that facilities streaming and visualization of data (video, depth, audio and skeleton data) from remotely connected Microsoft Kinect devices. The streamed video and depth data are reconstructed on the receiving side and rendered inside a 3D virtual environment that allows simultaneous connection from multiple sites. The client application includes a visualization module, which displays user's real-time generated 3D avatar with overlaid movement information (i.e., skeleton), and measurement module, which performs real-time analysis of the streamed skeleton data (see Figure 3). The original implementation sent data packets only through TCP/IP and was thus highly dependent on available network bandwidth and latencies.

The client user interface for Tele-MFAsT with KinectRTC is divided in three sections that provide the functionality needed to establish the connection between a remote user and a physiotherapist:

1. Connection controls. To select the server which the system connects to.
2. Data send controls. To select first, what kind of data will be sent (video, audio, depth information and skeletons). The other client will be able to show information depending on this selection. And next, to select a peer from the list and the connection with it established.
3. Remote visualization. With this option the remote 3D avatar can be hidden and the interface will only show the remote skeleton.

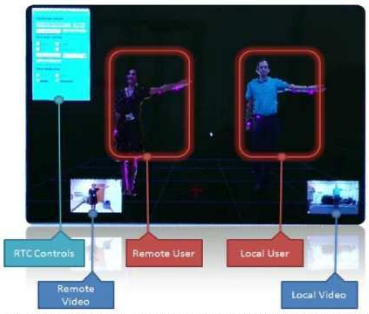

Figure 3: Tele-MFAst display output with KinectRTC user interface

2) *KiReS*

KinectRTC was also integrated in KiReS [27] a telerehabilitation system developed at the University of the Basque Country in order to test its operation within a different framework. KiReS is a Kinect based tele-rehabilitation system that places special emphasis on the provision, for physiotherapists and users, of a friendly and helpful interface [27]. KiReS allows the physiotherapists to define sets of exercises by recording themselves in front of Kinect. The physiotherapists can thus define a variety of exercises applicable to many different health conditions. The exercise interface for the patient displays the recorded movement of the therapist presented via a 3D avatar. Simultaneously the patient can observe their own avatar's movement based on captured skeleton data while receiving feedback on the performance in comparison to the physiotherapist's avatar.

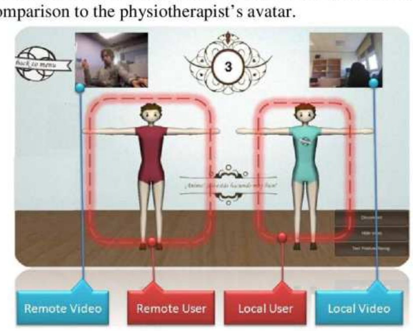

Figure 4: KiReS display output with KinectRTC user interface

The KinectRTC version of KiReS extends the functionality of the system by connecting the user and physiotherapist in real time via streaming video, audio and skeleton data. The updated user interface provides the users with a teleconference-like interface where local and remote video are displayed atop of the 3D avatars animated with the streamed skeleton data (see Figure 4).

D. KinectRTC at work

KinectRTC was tested in both local and remote networking environments to evaluate the performance of the communication implemented via WebRTC. All the test results presented in this paper were obtained using the Tele-MFAsT system with KinectRTC. The client application showed a graphic interface (see Figure 4) displaying the KinectRTC control menu, remote and local video streams at the bottom of the window, and the real-time skeletons with 3D body meshes of both users (remote user on the right and local user on the left).

Local tests were performed beforehand during the development and integration of Kinect RTC in Tele-MFAsT. To test the remote networking performance, several test sessions were performed between UC Berkeley (Berkeley, CA) and UC Davis Medical Center (Sacramento, CA) with approximate distance of 110 km. To further evaluate the performance of the framework for long distance interaction, KinectRTC system was tested between UC Berkeley and the University of the Basque Country UPV/EHU, Spain, where the distance is approximately 9000 km. In this paper the results of the latter set of experiments are presented (section IV) since they more faithfully represent the network conditions in a typical remote scenario where there is less quality control over the network conditions. The tests were performed on three different days establishing four calls per day. Each experimental session included two calls that included transmission of audio, video, skeleton data and depth images and two calls that did not include the depth data, which represented a significant amount of data transfer size. Both sides used Tele-MFAsT system with KinectRTC client. The server was always running on the UPV/EHU side.

IV. PERFORMANCE EVALUATION

KinectRTC puts a special emphasis on creating stable multimedia real-time communication using Kinect as the main source of audio, video and data. As WebRTC allows sending arbitrary data, this feature fits the need of transmitting depth maps and skeleton data when working with Kinect. However WebRTC does not manage data channels the same way it does with audio and video streams which are optimized for teleconferencing. Therefore KinectRTC data exchange over the binary channels requires the analysis of its performance.

The metrics used in this analysis were collected on both sides of the connection. Audio and video streams data were taken from WebRTC stats report tools and data stream stats were taken manually through the application (as WebRTC does not implement DataChannel stats recollection yet). The following metrics from each stream type were recorded:

Table 1 – Collected performance metrics

Audio and Video
Bytes sent/received
Packets sent/received/lost
Current Delay (ms)
(Round-Trip delay Time) RTT
Video
Available send/receive bandwidth
Target/Actual encoding bit rate
Frame height/width
Frame rate received
Data
Packet timestamp
Packet type
Packet size
Packets sent/received/lost

The tests showed that most delays occurred when receiving the depth images. Tele-MFAsT was thus unable to render the 3D avatar in synchrony with the RGB video data and the delay affected to all the binary data: camera parameters and skeletons included. Both video and audio had only minimal latencies. When depth maps were removed, the multimedia communication was much smoother in real-time. The Kinect skeletons and camera parameters, however, were still sent and, in this case, there was no noticeable delay for the real-time visualization.

Table 2 – Data size per second[1]

	Mean packet size (bytes)	Mean packets	%Total	%Total (no depth)
Audio	104.14	50.46	1.78%	2.88%
Video	960.88	124.41	40.59%	65.55%
CParam	352	30	3.59%	5.79%
Skel	1567	30	15.96%	25.78%
DepthMap	3738.4	30	38.08%	------

Table 2 shows the registered size statistics of the different types of data that KinectRTC can stream. Video and audio packets have a variable size during a connection as their quality is adapted according to the network state. The binary data packets, Camera Parameters (CParam) and skeletons (Skel), are data structures with fixed size since they always include the same number of parameters. The size of the depth maps, however, changes considerably depending on the captured scene. The size of the compressed depth map packet depends on the uniformity of the depth represented in a single frame. Large variance between the depth information in different pixels will result in larger packet size. In our scenario, we send the depth map with segmented silhouette of the user, therefore, the size mostly depends on how close the user is to the Kinect. During a typical interaction with the system, the depth map had a stable size as the user usually stayed at the same distance from Kinect. The average depth map size during the tests was 3.65 kB with peaks from 2.47 kB to 10.53 kB.

[1] Mean across all the experiments performed.

The last two columns in Table 2 present the relative size of each type of packet with respect to the total data sent in one second with and without depth maps respectively. The results show that sending depth maps increases the required bandwidth to 38.08% of the total data transfer, which is very close to the size of the streamed video data (40.59%). The binary data packets (CParam, Skel and DepthMap) represent less than the 60% of the total transferred data when sending depth maps and around 32% when depth maps are excluded.

Table 3 summarizes the registered packet loss during the four remote tests. These results are consistent with the users experience during the tests. While video and audio streams remained stable at both locations, at the EHU side binary data delay was considerably larger during tests 1 and 3. High percentage of the skeleton and depth packages sent to EHU were lost). In the two tests, the results demonstrate that there was not only a severe delay in data transfer of depth maps, but there was also a very high packet loss rate. In both tests with depth maps included the performance of the network was better from UPV/EHU to UC Berkeley than from UC Berkeley to UPV/EHU. Furthermore, we can observe that WebRTC kept the video and audio streams stable while binary data packets were dropped or delayed. Alternatively tests 2 and 4 without sending depth maps, show a very low rate of packets lost in audio, video and skeletons.

Table 3 – Packets lost[2]

	Video		Audio	
Receiver ►	BER	EHU	BER	EHU
Test 1	0.01%	0.11%	0.00%	0.14%
Test 2[3]	0.01%	0.00%	0.02%	0.04%
Test 3	0.01%	0.04%	0.01%	0.14%
Test 4[3]	0.02%	0.01%	0.00%	0.03%

	Skeleton		DepthMap	
Receiver ►	BER	EHU	BER	EHU
Test 1	0.04%	47.13%	0.18%	57.99%
Test 2[3]	0.00%	5.71%	---	---
Test 3	0.14%	35.09%	0.14%	48.96%
Test 4[3]	0.00%	0.62%	---	---

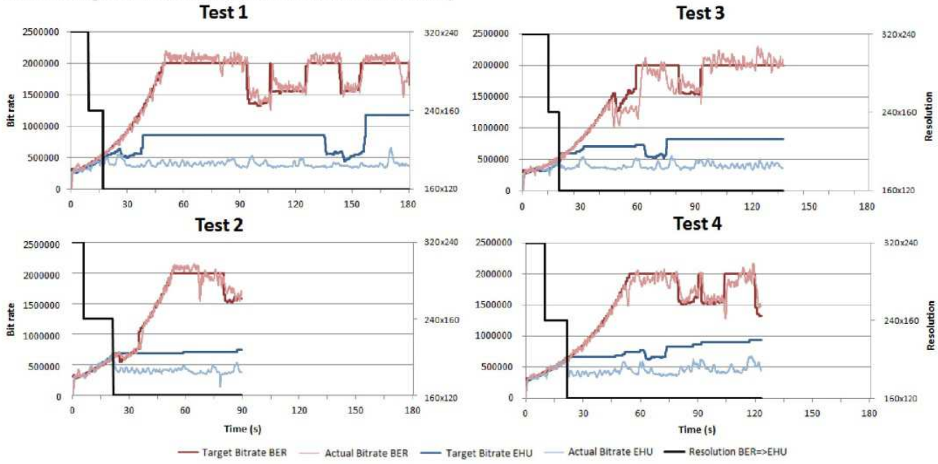

Figure 5: Target bit-rate vs actual bit-rate measured during tests and video resolution adaptation in Berkeley side

Figure 5 shows the target encoded bit rate and the actual encoded bit rate for the connection. In all the experiments KinectRTC detected more available bandwidth from UPV/EHU to UC Berkeley, making the video bit rate higher for that connection in all the tests. The bit rate data demonstrates how the target bit rate is modified based on the state of the network. In the case of video transmission, the video frame resolution is automatically reduced to accommodate the current network bandwidth. The video stream EHU=>BER was stable at a 320x240 resolution, while the video stream BER=>EHU was reduced twice until it reached the resolution of 160x120 (Figure 5), even when the depth maps were not included.

Figure 6 shows how the delay measured in audio and video streams evolves during a connection. When starting the connection there is usually a peak in audio delay that lasts a few seconds, after that it drops and the delay remains relatively stable. The delay fluctuates from 60 to 130 ms for audio and from 23 to 27 ms for video, keeping the latency between audio and video within a range that guaranties the necessary QoS for real-time multimedia communication [33].

[2] The percentage of packets that did not arrive at the receiver.
[3] Tests performed without sending depth maps.

These results were common for the different tests performed independently from the use of the data channel.

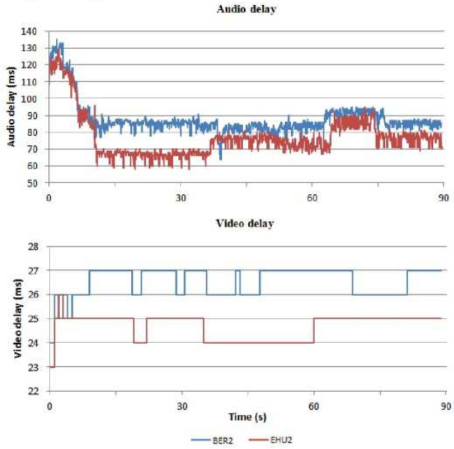

Figure 6: Time series of measured audio and video delay during test 2

Figure 7 and Figure 8 show the average audio and video delays measured at both locations during the tests. The delay was similar, independently from the type of binary data sent. It can be observed that there is no significant difference between tests 1 and 3 and tests 2 and 4. Even when the delay was present in the binary data channels, the audio and video performance was unaffected.

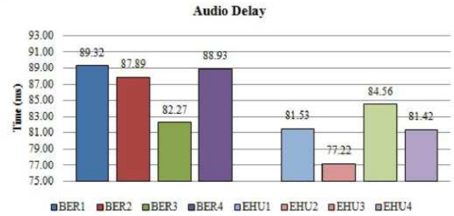

Figure 7: Average audio delay

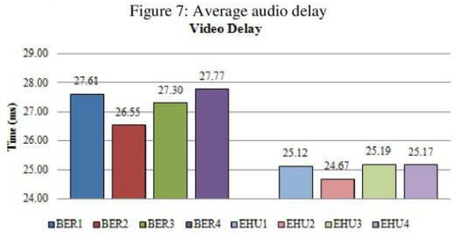

Figure 8: Average video delay

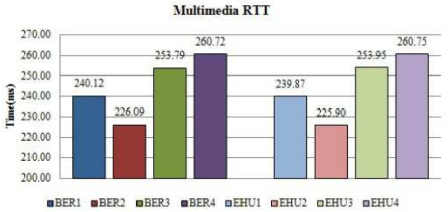

Figure 9: Average multimedia RTT

Figure 9 shows the average multimedia (video+audio) RTT. The results show that the round trip delay was on average between 220ms and 260ms. The multimedia RTT results are consistent with the previous analysis, even in those cases where delay was experienced in data streaming (skeletons and depth maps) audio and video streams kept stable and fluent.

V. Conclusion

Real-time multimedia transmission in telemedicine is a requirement for applications that facilitate remote and virtual meetings between the health provider and patient. Efficient and robust real-time communication is difficult to achieve on various network configurations without degrading the Quality of Service (QoS) which largely depends on the available bandwidth and the state of the network. In addition, other network elements such as firewalls and NATs can prevent these systems from working reliably or working at all in some of the environments. In this paper, KinectRTC is proposed as an innovative tele-rehabilitation framework that allows for streaming of real-time audio, video and other data obtained from a Kinect camera. Kinect RTC has been integrated with two previously developed platforms for rehabilitation. The results of the networking experiments show that KinectRTC can provide the basis for remote physical therapy with a reliable transmission of diverse medical data. Nevertheless in an unfavorable scenario, such as the network tests reported in this paper, it has been observed that binary data transmission, in particular data corresponding to depth images, generates delays and packet losses. Although interaction on such long distances is unlikely for the typical tele-rehabilitation, there are other applications in healthcare that may require efficient transmission of data in such scenarios (e.g., remote medical intervention in combat injuries). In summary, the analysis shows the capability of KinectRTC framework to adapt to various network conditions by taking advantage of WebRTC multimedia streaming performance. In case of Kinect depth data, there is significant burden on the bandwidth as the WebRTC does not provide the level of adaptation of data transfer through the binary channels that provides for video or audio streams. The users of KinectRTC therefore have an option to choose which data channels are being transmitted depending on the available resources and requirements of the client application. As it is the case with KiReS, only skeletal data is required alongside the multimedia stream to provide remote interaction via 3D avatars.

To address these issues, we are planning to implement adaptive depth data compression which can balance between the required accuracy of data and available bandwidth. Wu et al. developed a streaming engine that exploits the Color+depth representation enhancing it with Level of Detail (CZLoD) [34]. The authors measured the just noticeable degradation (JNDG) and just unacceptable degradation (JUADG) in a user study. Using these thresholds multimedia streams could be adapted to match user perception in real-time for the given available network bandwidth and user conditions. In our future work, we will further investigate how potential network delays affect the interaction and the movement feedback during therapy sessions.

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F. TrhOnt: Building an ontology to assist rehabilitation processes

- Title: TrhOnt: Building an ontology to assist rehabilitation processes
- Authors: Idoia Berges, David Antón, Jesús Bermúdez, Alfredo Goñi and Arantza Illarramendi
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TrhOnt: Building an ontology to assist rehabilitation processes

Idoia Berges, David Antón, Jesús Bermudez, Alfredo Goñi and Arantza Illarramendi

ABSTRACT

Objective: To introduce *TrhOnt*, a service ontology that can assist physiotherapists in their daily tasks via reasoning supported by semantic technology.

Materials and Methods: The ontology was developed following the NeOn Methodology. It integrates ontological (e.g. FMA ontology) and non-ontological resources (e.g a database of movements, exercises and treatment protocols) as well as additional knowledge.

Results: We demonstrate how the ontology fulfills the purpose of providing a reference model for the representation of the physiotherapy-related information that is needed for the whole physiotherapy treatment of a patient, since he steps for the first time into the physiotherapist's office, until he is released. More specifically, we present the results for each of the Intended Uses listed in the Ontology Requirements Specification Document, and show how *TrhOnt* can answer the competency questions defined within that document. Moreover we detail the main steps of the process followed to build the *TrhOnt* ontology in order to facilitate its reproducibility in a similar context.

Discussion and conclusion: *TrhOnt* has achieved the purpose of allowing for a reasoning process that changes over time according to the patient's state and performance.

Key words: Ontologies, Knowledge Representation, Clinical Decision Support Systems in Physiotherapy

OBJECTIVE

Whenever a patient is treated in a physiotherapy unit some amount of information is generated, which includes the clinical data relevant to the current situation of the patient, as well as information regarding his personal and family history, habits, the evolutionary process, treatment and recovery. As it has been shown in other scenarios related to biomedicine[1-4], semantic technologies such as ontologies can play a relevant role in transforming that information into knowledge that facilitates the work of the physicians. In this paper we present *TrhOnt*, an ontology whose goal is to assist physiotherapists in the following daily tasks:

- Recording and searching information about the items that compose the physiotherapy record of a patient.
- Defining treatment protocols for a specific disorder, by selecting the exercises that must be performed in each phase of the protocol.
- Identifying in which phase of a treatment protocol a patient is at some specific moment.
- Identifying which exercises are most suitable for a patient at some specific moment, given all the information that it is known about him.

BACKGROUND AND SIGNIFICANCE

One of the largest research efforts in the area of knowledge representation is providing languages to represent information in a structured way so that reasoning can be performed on it. These languages should have enough expressive power, have a formal semantics and be decidable[5]. Description Logics (DLs)[6] are a family of such formalisms that provide the basis for ontology languages such as OWL[7], being an ontology "*an attempt to represent conceptualizations that match the true nature of some subdomain of reality, explaining which entities exist in the world, how these entities can be classified taxonomically and how they are related with one another*"[8].

The use of ontologies is gaining relevance in medicine, and as a result several ontologies have been developed to cover medical related information. One example is the Foundational Model of Anatomy (FMA)[9], whose current release contains over 100,000 classes and properties for the representation in OWL of the phenotypic structure of the human body. Ontologies have been also used for clinical decision support in health-related fields. Sahoo et al.[10] developed an epilepsy and seizure ontology (EpSO) using a four-dimensional epilepsy classification system. This ontology is used in a suite of tools to store patient information, extract structured information and identify patient cohorts. In Haguigui et al.[11] an ontology for the support of medical emergency decision making during mass gathering events is presented. The closest works to ours are those of Bouamrane et al.[12] and Sesen et al.[13]. In [12] ontologies are used in the development of a preoperative assessment system to recommend preoperative tests to patients while in [13] a lung cancer ontology for categorizing patients and producing guideline-based treatment recommendations is described.

MATERIALS AND METHODS

In order to achieve the reasoning goals described in section *Objective* we implemented one OWL ontology following the NeOn methodology[14]. The NeOn Methodology framework presents a set of scenarios for building ontologies and ontology networks. These scenarios are decomposed into several processes or activities, and can be combined in flexible ways to achieve the expected goal (Fig. 1).

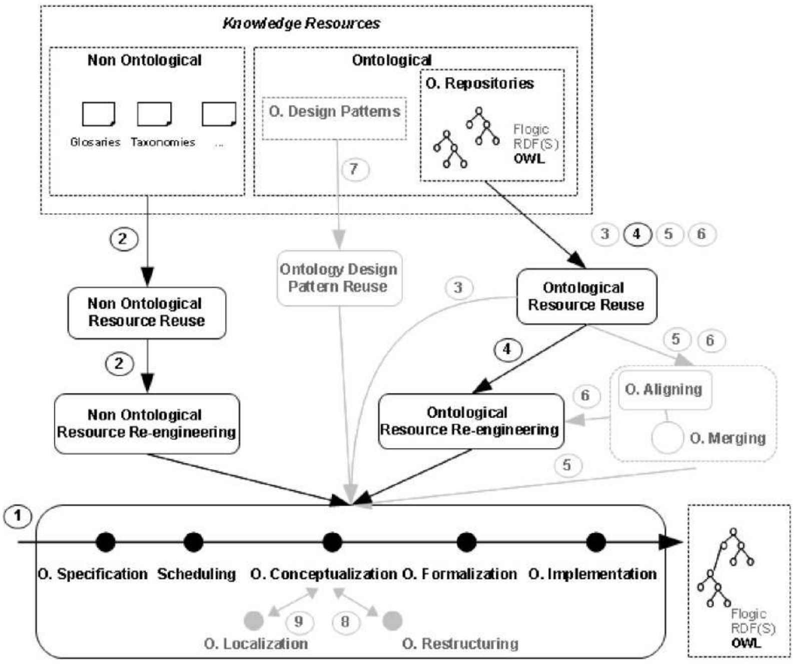

Fig. 1 Scenarios for building ontologies and ontology networks, adapted from[14]. In bold, the scenarios that were used in our development.

In our case three scenarios have been combined to obtain the current version of the ontology[1], which contains over 2,300 classes and properties to represent:

- The physiotherapy record of a patient: scenario 1
- Movements, exercises and treatment protocols: scenario 4
- A selected part of the human body. We focused on the glenohumeral joint and the body parts that are related to it: scenario 2
- Other relevant information for the physiotherapeutic domain: scenario 1

A detailed account of how each of those scenarios was applied is presented next.

Scenario 1: From Specification to Implementation

This scenario is composed of the five core activities to be performed in the development of any ontology: ontology requirements specification, scheduling, conceptualization, formalization and implementation.

- *Ontology requirements specification*: It produces as output the Ontology Requirements Specification Document (ORSD), where information such as the purpose, the scope and the intended uses of the ontology is described (Table 1). Special attention must be paid to the definition of groups of competency questions, which are the set of questions that the ontology must be able to answer. In our case, competency questions related with physiotherapy records, body parts and treatment protocols were defined, as well as some general-purpose competency questions that either fall in more that one of those categories or do not fall in any of them.

Table 1 Excerpt of the Ontology Requirements Specification Document defined for our ontology

1. Purpose
The purpose of the *TrhOnt* ontology is to provide a reference model for the representation of the physiotherapy-related information that is needed for the whole physiotherapy treatment of a patient, since he steps for the first time into the physiotherapist's office, until he is discharged.
2. Scope
The ontology will focus on physiotherapy issues related to the glenohumeral joint.
3. Implementation language

[1]http://bdi.si.ehu.es/bdi/demos/ontology/

The ontology has to be implemented in OWL

4. Intended end users

- *User 1*: Physiotherapists

5. Intended uses

- *Use 1*: To record and search information about the items that compose the physiotherapy record of a patient.
- Use 2: To help the process of defining general treatment protocols for a specific disorder, by selecting the exercises that must be performed in each phase of the protocol.
- Use 3: To help the process of identifying in which phase of a treatment protocol a patient is at some specific moment.
- Use 4: To identify which exercises are most suitable for a patient at some specific moment given all the information that it is known about him.

6. Ontology requirements

(a) Non-functional requirements (not applicable)

(b) Functional requirements: Groups of competency questions

CQG1: Physiotherapy record-related competency questions:

- *CQ1.1*: What is the patient's age?
- *CQ1.2*: Which health issue does the patient report?
- *CQ1.3*: Which are the patient's recovery goals?
- *CQ1.4*: How much pain does the patient report on the Visual Analogue Scale (VAS)?
- *CQ1.5*: Which results are obtained from the exploration of the joint movement of the patient?
- *CQ1.6*: What is the physiotherapy diagnostics of the patient?
- *CQ1.7*: Which is the family and personal past history of the patient?
- ...

CQG2: Body-related competency questions

- *CQ2.1*: Which are the body parts that compose a more general body part?
- *CQ2.2*: Which is the laterality of a specific body part?
- ...

CQG3: Treatment protocol-related competency questions:

- *CQ3.1*: Which is the type of a movement?
- *CQ3.2*: Which body part does a movement refer to?
- *CQ3.3*: Which range of movement does a movement cover?
- *CQ3.4*: Which movements compose an exercise?
- *CQ3.5*: Which exercises compose a phase of a treatment protocol?
- *CQ3.6*: Which are the conditions that an exercise must fulfill to be a candidate exercise for a phase of a treatment protocol?
- ...

CQG4: General competency questions:

- *CQ4.1*: Which are the conditions that a patient must fulfill in order to be in a phase of a treatment protocol?
- *CQ4.2*: Which phase is a patient in?
- *CQ4.3*: Which exercises are recommended for a patient at some specific moment?
- *CQ4.4*: Which exercises are contraindicated for a patient at some specific moment?
- Which exercises do patients usually perform bad?

7. Pre-glossary of terms

Patient, goal, joint, movement, exercise, ...

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Once the ORSD was generated, we performed a search for candidate knowledge resources. The search was performed following the activities defined in Scenario 2 and Scenario 4 of NeOn, which will be explained later. As a result the *KiReSOnt* and *GlenoFMA* ontologies were obtained.

- *Scheduling:* The selected ontology network life cycle was the Six-Phase Waterfall, described in[14], because apart from the initiation, design, implementation and maintenance phases that 4-phase cycles usually include, it integrates a reuse phase and a re-engineering phase.
- *Conceptualization and Formalization*: Both activities were performed together to obtain a formal model of the ontology, where all the classes and properties that are needed to answer the competency questions were described by means of DLs (see section Results).
- *Implementation*: The formal model was implemented in the ontology language OWL using Protégé[15].

Scenario 2: Reusing and Re-engineering Non-Ontological Resources

This scenario was used to select non-ontological resources that represent information related to joint movements, rehabilitation exercises and treatment protocols for disorders of the shoulder, and convert that information into one ontology. Two processes were carried out: reuse and reengineering. The reuse process comprises three activities:

- *Search non-ontological resources*: Among others, a document about exercises and treatment protocols for rehabilitation after shoulder dislocation from NHS was found[16]. Moreover, a database of shoulder movements and exercises from a Kinect-based telerehabilitation system[17] was considered, as well as a set of treatment protocols for several shoulder-related disorders provided by expert physiotherapists. We restrict the description of the following point to these resources.
- *Assess the set of candidate non-ontological resources:* We performed the assessment keeping in mind the intended uses of the target ontology (Table 2). In the case of resources that contain movements the quality of their description was assessed (i.e. does the movement indicate the initial and final position? Does it indicate the ROM?). In the case of resources that contain exercises, the quality of the description and the easiness to identify single movements within those exercises was evaluated. Finally, concerning resources that contain treatment protocols,

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we valued the number of disorders that were considered, as well as the existence of phases in those protocols and conditions to classify patients in phases.

- *Select the most appropriate non-ontological resources:* We selected the database of the Kinect-based telerehabilitation system as a resource for movements and exercises, due to the richness of their descriptions, which provide great information for our reasoning purposes. Moreover, we selected the pool of treatment protocols provided by expert physiotherapists since it covers a wide range of disorders with definition of phases and their conditions (Fig. 2).

Table 2 Summarized assessment of candidate non-ontological resources. A tick (✓) indicates that the resource fulfils the requirement, an X that the resource does not fulfill it, and a hyphen (-) that the requirement does not apply to that resource

	NHS document	Database Kinect-based system	General treatment protocols
Movements: Quality of description	-	✓	-
Exercises: Quality of description	✓	✓	-
Exercises: Easiness to identify movements	X	✓	-
Protocols: N. of disorders	1	-	10
Protocols: Phases	✓	-	✓
Protocols: Transition conds.	X	-	✓

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Movement 2.1.5d Abduction of the Shoulder 90°

Plane: Frontal **Range of Motion (ROM):** 0 to 90°

Initial posture	Execution	Final posture
		
Arms on the sides.	Move the arm upwards with the elbow in extension and the forearm in neutral pronosupination .	Arm remains separated with the elbow in extension and the forearm in neutral pronosupination.

Treatment for limited flexion of the glenohumeral joint

Phase	Exercises	Repetitions	Conditions
1	...	...	...
2	211a, 211b, 211c, 211d, 212a, 212b, 213a, 213b, 214a, 214b, 215a, 215b, 215c, 215d, 216a	4x3	Value lower than 3.0 in the VAS scale. At least one of the following: - ROM<90° in flexion - ROM<25° in extension - ROM<90° in abduction - ROM<27° in adduction - ROM<45° in internal rotation - ROM<55 in external rotation
3	211c, 211d, 211e, 212b, 212c, 213b, 213c, 214b, 214c, 214d, 215c, 215d, 215e, 216a, 217a, 217b, 217c, 218a, 218b, 218c, 218d, 218z	4x3	Reports no pain during the performance of exercises. At least one of the following: - 90°≤ROM<144° in flexion - 25°≤ROM<40° in extension - 90°≤ROM<144° in abduction - 27°≤ROM<36° in adduction - 45°≤ROM<72° in internal rotation - 55°≤ROM<88° in external rotation - ROM<32° in horizontal abduction - ROM<112° in horizontal adduction
...	...	...	...

Fig. 2 Example of movement and excerpt of treatment protocol from the selected non-ontological resources.

After the reuse process, the re-engineering process was carried out to obtain an ontology from the gathered knowledge. Three activities were performed:

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- *Non-ontological resource reverse engineering*: the resources were analyzed to identify their underlying components. In the case of movements their name, type (flexion, extension, internal/external rotation, (horizontal) abduction, (horizontal) adduction), range of motion, plane (frontal, sagittal, transverse), initial/final posture, execution and affected body location were identified. It was also detected that in some cases a single movement is composed of more than one submovements that take place simultaneously but with different values for the {type, ROM, location} triplet. In the case of exercises their name and sequence of movements were considered. As for treatment protocols, their name, related disorder, sequence of phases (which are made up of collection of exercises), conditions of the phases, number of repetitions of each exercise and number of times the whole phase must be repeated in the same session were identified.
- *Non-ontological resource transformation:* A conceptual model relating the underlying components identified in the previous activity was generated.
- *Ontology forward engineering:* A formal model expressed in DLs was generated from the conceptual model and later implemented in OWL using Protégé (see section Results). The resulting ontology, *KiReSOnt*, is the output of this scenario.

Scenario 4: Reusing and Re-Engineering Ontological Resources

This scenario was used to select ontological resources that represent the glenohumeral joint and related body parts. As in the previous scenario, reuse and re-engineering were performed. More specifically, four activities were carried out in the reuse process:

- *Ontology search*: The search for an ontology that covers only the glenohumeral joint and its related body parts was unsuccessful, so we expanded the search to ontologies that cover the whole human body. Two candidate ontologies were selected: OpenGALEN[18] and FMA[19].
- *Ontology assessment*: The assessment was performed taking into account five criteria: Coverage, Understandability effort, Integration effort, Reuse economic cost and Reliability. We restricted the assessment to the Human Anatomy extension of OpenGALEN. In the case of FMA, version 4.0 was assessed (Table 3).

Table 3 Summarized assessment of ontological resources

	Requirements	OpenGALEN	FMA
Coverage	It must cover at least the glenohumeral joint and its related body parts at great detail	✓	✓
Understandability effort	Pruning supported by a physiotherapist will be needed to obtain a module about the glenohumeral joint. Thus the structure of the ontology in ontology development tools such as Protégé must be easy to understand.	Too many classes defined at the top level, it makes it difficult to understand the actual hierarchy. Many classes have very long names, which are difficult to read.	✓
Integration effort	It should be easy to integrate the candidate ontology with the ontology being developed. Moreover its implementation must adapt to the reasoner being used, and be logically satisfiable. In our case it is sufficient if the glenohumeral joint module is satisfiable.	✓	It includes unsatisfiable classes, but it is known that satisfiable modules can be obtained from it[20,21]
Reuse economic cost	It refers to the cost of accessing and using the ontology, including licensing costs.	30 man-hours. No licensing fees.	20 man-hours. No licensing fees.
Reliability	The candidate ontology should come from reliable sources	✓	✓

- *Ontology comparison*: Both ontologies cover the domain of the glenohumeral joint to an appropriate extent. Moreover, we think that the hierarchy and nomenclature used in FMA are much clearer than those in OpenGALEN, which reduces the expected man-hours of work and thus the reuse economic cost. Since an implementation of both ontologies in OWL exists, both of them are suitable for OWL reasoners. However FMA-OWL includes unsatisfiable classes[22,23], as opposed to OpenGALEN, although the literature has proved that fully

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satisfiable modules can be obtained from it[21]. Both ontologies are considered reliable since they were developed by reputable institutions and have been used in multiple projects throughout the years[24-27].

- *Ontology selection*: Given the need of involving a physiotherapist for pruning the ontology, we opted for selecting the FMA due to its clarity, always keeping in mind that we would need to check the satisfiability of the glenohumeral joint module once extracted.

After the reuse process, the re-engineering process was carried out to obtain the glenohumeral joint module. More precisely, two activities were performed:

- *Ontology re-specification:* The scope of the FMA ontology was modified to consider just the glenohumeral joint and its related classes.
- *Ontology re-conceptualization:* We pruned the FMA ontology with the help of a module extractor[28,29] and a physiotherapist to obtain the glenohumeral joint module, *GlenoFMA*, used to represent the concepts about rehabilitation processes of shoulder pathologies. The module extractor works selecting concepts that are connected to a list of concepts passed as an argument. This way we obtained a module of classes and properties composed of elements connected between them. In our case we performed an upper hierarchy extraction using "GlenoHumeral Joint" as the only argument for the extraction process. A concept selected this way will always be connected with some other hierarchically or by a property. Then we performed a clean-up process to remove those concepts that were clearly not related with upper limbs (e.g. toe, ankle, pelvis). After that, we applied another round of the module extractor to remove "orphan" terms that might be left after the removal. Finally, this new module was presented to a physiotherapist that checked it manually, and validated its content removing those terms he considered inadequate for the representation of upper limb pathologies in rehabilitation. This module proved to be free of unsatisfiable classes.

RESULTS

The resulting ontology must cover the four intended uses mentioned in the ORSD, which are related to the competency questions listed in that same document.

Results for Intended Use 1

In this intended use the ontology is regarded as a means to record and search information about the items that compose the physiotherapy record of a patient. It must be able to answer the competency questions in groups CQG1 and CQG2.

The most important class, around which everything else was constructed, is `PhysiotherapyRecord` (Fig. 3a). Each `Patient` is related to his physiotherapy record(s), which is composed of a set of answers. For each of the competency questions of CQG1 a representation of its answer was defined within the physiotherapy record. For example class `CA1.4` is used to represent the answer to "*CQ1.4: How much pain does the patient report on the VAS?*", and includes the necessary properties (`hasVASvalue`) to store the patient's response as well as restrictions in its type and/or value (`double[≥0.0,≤10.0]`). When needed, other classes related to the terms in the competency questions were defined to represent more complicated concepts (e.g. `MovementExploration`).

Recorded answers about a specific patient are represented as instances of classes of the ontology. Hence, the information about patient with ID *patient2015* seen in Fig. 3b is transformed, among others, into the set of triples in Fig. 3c.

Competency questions in CQG2 can be answered by means of the *GlenoFMA* part of the ontology that was created in Scenario 4. For example, one relevant property in that ontology is `constitutional_part`, used to describe meronymy relationships between body parts (Fig. 3d).

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a)

$$\mathtt{Patient} \sqsubseteq \exists\mathtt{hasRecord.PhysiotherapyRecord}$$
$$\mathtt{PhysiotherapyRecord} \sqsubseteq \exists\mathtt{hasAnswer.Answer}$$
$$\mathtt{CA1.1} \equiv \mathtt{Answer} \sqcap \exists\mathtt{hasAge.integer}[\geq 0]$$
$$\mathtt{CA1.4} \equiv \mathtt{Answer} \sqcap \exists\mathtt{hasVASvalue.double}[\geq 0.0, \leq 10.0]$$
$$\mathtt{CA1.5} \equiv \exists\mathtt{hasMovementExploration.MovementExploration}$$
$$\mathtt{MovementExploration} \sqsubseteq \exists\mathtt{hasMovementType.MovementType} \sqcap \exists\mathtt{hasLocation.Joint} \sqcap \exists\mathtt{hasROMvalue.double} \sqcap \exists\mathtt{hasPain.boolean}$$
$$\mathtt{MovementType} \equiv \mathtt{Flexion} \sqcup \mathtt{Extension} \sqcup \mathtt{ExtRotation} \sqcup \mathtt{IntRotation} \sqcup \mathtt{Abduction} \sqcup \mathtt{Adduction} \sqcup \mathtt{HorizAbduction} \sqcup \mathtt{HorizAdduction}$$
$$\mathtt{CA1.7} \equiv \exists\mathtt{hasPastHistory.FamilyOrPersonalPastHistoryItem}$$
$$\mathtt{FamilyOrPersonalPastHistoryItem} \equiv \mathtt{PathologicalCondition} \sqcap \exists\mathtt{hasPatient.(Self} \sqcup \mathtt{Relative)} \sqcap \forall\mathtt{hasIntensity.Intensity} \sqcap \forall\mathtt{hasTimespan.Timespan}$$
$$\mathtt{DislocationOfLeftGlenohumeralJoint} \sqsubseteq \mathtt{PathologicalCondition}$$

b)

c)

⟨patient2015	rdf:type	Patient⟩
⟨patient2015	hasRecord	record2015⟩
⟨record2015	rdf:type	PhysiotherapyRecord⟩
⟨record2015	hasAnswer	ca1.4⟩
⟨ca1.4	rdf:type	CA1.4⟩
⟨ca1.4	hasVASvalue	0.0⟩
⟨record2015	hasAnswer	ca1.5⟩
⟨ca1.5	rdf:type	CA1.5⟩
⟨ca1.5	hasMovementExploration	movexp1⟩
⟨movexp1	rdf:type	MovementExploration⟩
⟨movexp1	hasMovementType	flexion⟩
⟨movexp1	hasLocation	leftGlenoJoint2015⟩
⟨leftGlenoJoint2015	rdf:type	GlenohumeralJoint⟩
⟨movexp1	hasROMvalue	80⟩
⟨movexp1	hasPain	false⟩
⟨record2015	hasAnswer	ca1.7⟩
⟨ca1.7	rdf:type	CA1.7⟩
⟨ca1.7	hasPastHistory	phi1⟩
⟨phi1	rdf:type	DislocationOfLeftGlenohumeralJoint⟩
⟨phi1	hasPatient	self⟩

d)

$$\mathtt{GlenohumeralJoint} \sqsubseteq \exists\mathtt{constitutional\_part.`Coracohumeral\ ligament'}$$
$$\mathtt{GlenohumeralJoint} \sqsubseteq \exists\mathtt{constitutional\_part.`Glenoid\ labrum\ of\ scapula'}$$

Fig. 3 Results for intended use 1.

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Results for Intended Use 2

In the second intended use the ontology is seen as a means to help the process of defining general treatment protocols for a specific disorder, by selecting the exercises that must be performed in each of the phases of the protocol. It must be able to answer the competency questions in group CQG3. This part of the ontology was the one created from non-ontological resources in Scenario 2.

Representation of movements, exercises and treatment protocols

A `Movement` is represented by its initial and final postures, and is composed of one or more `Submovement`s that take place simultaneously within that movement. The latter is the case for movements that occur in more than one anatomical plane (e.g. diagonals) or which require the movement of two joints at the same time (e.g. both right and left glenohumeral joints). For each `Submovement` its `Joint`, `MovementType` and `ROM` are indicated, which for example can be used to answer competency questions CQ3.1 to CQ3.3. Moreover, `Mov2.1.5d` and `Mov2.2.1z` are examples of movements with one and more submovements respectively (Fig. 4a).

```
a)
           Movement ≡ ∃hasComponent.Submovement
        Submovement ⊑ ∃hasLocation.Joint ⊓ ∃hasMovementType.MovementType ⊓
                      ∃hasROMmin.integer ⊓ ∃hasROMmax.integer
          Mov2.1.5d ≡ Movement ⊓ ∃hasInitialPosture.value{'Arms on the sides'} ⊓
                      ∃hasFinalPosture.value{'Arm remains separated...'} ⊓
                      ∃hasComponent.(Submovement ⊓ ∃hasLocation.GlenohumeralJoint ⊓
                      ∃hasMovementType.Abduction ⊓ ∃hasROMmin.value{0} ⊓ ∃hasROMmax.value{90})
          Mov2.1.5d ⊑ ∃hasName.value{'Abduction of the shoulder at 90 degrees'}
          Mov2.2.1z ≡ Movement ⊓ ∃hasInitialPosture.value{'The initial posture for...'} ⊓
                      ∃hasFinalPosture.value{'Arm flexed and adducted...'} ⊓
                      ∃hasComponent.(Submovement ⊓ ∃hasLocation.GlenohumeralJoint ⊓
                      ∃hasMovementType.Flexion ⊓ ∃hasROMmin.value{0} ⊓ ∃hasROMmax.value{180}) ⊓
                      ∃hasComponent.(Submovement ⊓ ∃hasLocation.GlenohumeralJoint ⊓
                      ∃hasMovementType.Adduction ⊓ ∃hasROMmin.value{0} ⊓ ∃hasROMmax.value{50}) ⊓
                      ∃hasComponent.(Submovement ⊓ ∃hasLocation.GlenohumeralJoint ⊓
                      ∃hasMovementType.ExtRotation ⊓ ∃hasROMmin.value{0} ⊓ ∃hasROMmax.value{90})
          Mov2.2.1z ⊑ ∃hasName.value{'Diagonal of flexion, adduction and external rotation'}

b)
           Exercise ≡ ∃hasInitialMovement.Movement
         Exer2.1.5d ≡ Exercise ⊓ ∃hasInitialMovement.(Mov2.1.5d ⊓ ∃hasNextMovement.Mov2.1.5d_inv)
    hasNextMovement ⊑ hasFurtherMovement

c) TreatmentProtFlexGlenoJ ≡ TreatmentProtocol ⊓ ∃hasInitialPhase.(Phase1FlexGlenoJ ⊓
                      ∃hasNextPhase.(Phase2FlexGlenoJ ⊓ ∃hasNextPhase.(Phase3FlexGlenoJ ⊓ ...)))
   Phase2FlexGlenoJ ≡ Phase ⊓ ∃hasInitialExercise.(Exer2.1.1a ⊓ ∃hasNextExercise.(Exer2.1.1b ⊓ ...)) ⊓
                      ∃hasSeries.value{4} ⊓ ∃hasConditions.Cond2FlexGlenoJ
    Cond2FlexGlenoJ ≡ ∃ROMFlex.double[<90.0] ⊓ ∃ROMExt.double[<25.0] ⊓ ∃ROMAbdu.double[<90.0] ⊓
                      ∃ROMAddu.double[<27.0] ⊓ ∃ROMIntRot.double[<45.0] ⊓ ∃ROMExtRot.double[<55.0] ⊓
                      ∃hasVASvalue.double[<3.0]

d)  CandExe2FlexGlenoJ ≡ Exercise ⊓ (
                      (∃hasInitialMovement.(MovFlexGJLessEqual90 ⊔ ∃hasFurtherMovement.MovFlexGJLessEqual90)) ⊔
                      (∃hasInitialMovement.(MovExtGJLessEqual25 ⊔ ∃hasFurtherMovement.MovExtGJLessEqual25)) ⊔
                      (∃hasInitialMovement.(MovAbduGJLessEqual90 ⊔ ∃hasFurtherMovement.MovAbduGJLessEqual90)) ⊔
                      (∃hasInitialMovement.(MovAdduGJLessEqual27 ⊔ ∃hasFurtherMovement.MovAdduGJLessEqual27)) ⊔
                      (∃hasInitialMovement.(MovIntRotGJLessEqual45 ⊔ ∃hasFurtherMovement.MovIntRotGJLessEqual45)) ⊔
                      (∃hasInitialMovement.(MovExtRotGJLessEqual55 ⊔ ∃hasFurtherMovement.MovExtRotGJLessEqual55))
                      )

  MovFlexGJLessEqual90 ≡ Movement ⊓ ∃hasComponent.(Submovement ⊓ ∃hasLocation.GlenohumeralJoint ⊓
                      ∃hasMovementType.Flexion ⊓ ∃hasROMmax.double[≤90.0])

    CandExe3FlexGlenoJ ≡ Exercise ⊓ (
                      (∃hasInitialMovement.(MovFlexGJLessEqual144 ⊔ ∃hasFurtherMovement.MovFlexGJLessEqual144)) ⊔
                      (∃hasInitialMovement.(MovExtGJLessEqual40 ⊔ ∃hasFurtherMovement.MovExtGJLessEqual40)) ⊔
                      (∃hasInitialMovement.(MovAbduGJLessEqual144 ⊔ ∃hasFurtherMovement.MovAbduGJLessEqual144)) ⊔
                      (∃hasInitialMovement.(MovAdduGJLessEqual36 ⊔ ∃hasFurtherMovement.MovAdduGJLessEqual36)) ⊔
                      (∃hasInitialMovement.(MovIntRotGJLessEqual72 ⊔ ∃hasFurtherMovement.MovIntRotGJLessEqual72)) ⊔
                      (∃hasInitialMovement.(MovExtRotGJLessEqual88 ⊔ ∃hasFurtherMovement.MovExtRotGJLessEqual88)) ⊔
                      (∃hasInitialMovement.(MovHorAbduGJLessEqual32 ⊔ ∃hasFurtherMovement.MovHorAbduGJLessEqual32)) ⊔
                      (∃hasInitialMovement.(MovHorAdduGJLessEqual112 ⊔ ∃hasFurtherMovement.MovHorAdduGJLessEqual112))
                      )

e)   Exer2.1.5d ⊑ Exe2FlexGlenoJ
```

Fig. 4 Results for intended use 2.

An `Exercise` is represented as a sequence of movements. Thus, every exercise must have an initial movement, which can be followed by another movement, and so on, as in the case of `Exer2.1.5d`.

This answers CQ3.4. Moreover, some other properties were defined, such as `hasFurtherMovement`, which links a movement with any other movement further on the sequence of movements within an exercise (Fig. 4b).

A treatment protocol is represented as a sequence of phases. Among others, each phase contains a sequence of exercises to be performed during that phase, as well as the conditions that indicate when a patient is in that phase. These conditions were indicated in terms of the ROMs that patients achieve and the pain they report (pain in general and pain during the performance of the exercises). In Fig. 4c the representation of the treatment protocol for limited flexion of the glenohumeral joint is presented.

It should be noticed that the set of movements, exercises and protocols in *KiReSOnt* can be extended by physiotherapists. Currently we are developing a graphical tool for this purpose.

<u>Selection of the exercises to be performed during a phase</u>

Whenever a physiotherapist wants to create a general treatment protocol, she can rely on the ontology to select the exercises for each phase. Once the number of phases of the protocol has been defined alongside the conditions of each phase, a new set of classification rules for the selection of candidate exercises are created from these conditions. Then, one ontology class is created automatically for each phase of the protocols based on the classification rules (Fig. 4d). For example, class `CandExe2FlexGlenoJ` represents the candidate exercises for phase 2 of the protocol for patients with limited flexion of the glenohumeral joint. Each of the `Mov*` classes in the definition refer to the movements that the exercise must have to be classified in `CandExe2FlexGlenoJ`. More precisely, `MovFlexGJLessEqual90` represents those movements of flexion of the glenohumeral joint with a ROM lower or equal to 90°. Any exercise that contains this movement (or any of the aforementioned `Mov*` movements) either as initial movement or later in the sequence is classified as `CandExe2FlexGlenoJ`, for instance `Exer2.1.5d`, and will be presented to the physiotherapist. If she selects the exercise, a new assertion is created (Fig. 4e), where `Exer2.1.5d` is no longer only candidate but also a proper exercise of phase 2 (it subsumes `Exe2FlexGlenoJ`). Classes for representing candidate exercises of other phases are defined likewise (see `CandExe3FlexGlenoJ`). Beware that one of the classes (`CandExe3FlexGlenoJ`) subsumes the other

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(CandExe2FlexGlenoJ), meaning that all the exercises classified as CandExe2FlexGlenoJ are also classified as CandExe3FlexGlenoJ, because at any point the physiotherapist should be able to select milder exercises, in order, for example, to warm the joint up.

Results for Intended Use 3

The third intended use gives response to some of the competency questions defined in CQG4. The ontology is used as a means to help the process of identifying in which phase of a treatment protocol a patient is at some specific moment. This is done by taking into account the results of the movement explorations of the patient at that time. As in the previous case, the classification is guided by the conditions specified in the phases of the protocols. In this case, conditions regarding the ROM and the pain are considered. Then, one ontology class is created automatically for each phase of each protocol based on the latter conditions. For example, in Fig. 5 the definition of the classes Patient2FlexGlenoJ and Patient3FlexGlenoJ can be seen, which represent those patients which are in phase 2 and 3 of the protocol to treat the limited flexion of the shoulder respectively. Each of the classes MovExplo* in the definition refers to one type of movement exploration that the patient may have had. For instance we present the definition of MovExploFlexGJLessThan90 to indicate an exploration of the flexion of the shoulder where the ROM achieved by the patient is below 90°. The other explorations are defined likewise. Thus, whenever a patient has a movement exploration that satisfies the definition of any of the MovExplo* classes in Patient2FlexGlenoJ and reports a value lower than 3.0 in the VAS, the patient will be classified as belonging to the class Patient2FlexGlenoJ.

```
Patient2FlexGlenoJ ≡ Patient ⊓ ∃hasRecord.(PhysiotherapyRecord ⊓ ∃hasAnswer.(CA1.4 ⊓ ∃hasVASvalue.double[<3.0]) ⊓
                     ∃hasAnswer.(CA1.5 ⊓ ∃hasMovementExploration.(MovExploFlexGJLessThan90 ⊔ MovExploExtGJLessThan25 ⊔
                     MovExploAbduGJLessThan90 ⊔ MovExploAdduGJLessThan27 ⊔ MovExploIntRotGJLessThan45 ⊔
                     MovExploExtRotGJLessThan55)))
MovExploFlexGJLessThan90 ≡ MovementExploration ⊓ ∃hasLocation.GlenohumeralJoint ⊓ ∃hasMovementType.Flexion ⊓
                     ∃hasROMmax.double[<90.0]
Patient3FlexGlenoJ ≡ Patient ⊓ ∃hasRecord.(PhysiotherapyRecord ⊓ ∃hasAnswer.(CA1.5 ⊓
                     ∃hasMovementExploration.((MovExploFlexGJBetween90And143 ⊔ MovExploExtGJBetween25And39 ⊔
                     MovExploAbduGJBetween90And143 ⊔ MovExploAdduGJBetween27And35 ⊔ MovExploIntRotGJBetween45And71 ⊔
                     MovExploExtRotGJBetween55And87 ⊔ MovExploHorAbduGJLessThan32 ⊔ MovExploHorAdduGJLessThan112) ⊓
                     ∃hasPain.value{false})))
```

Fig. 5 Results for intended use 3.

For instance, if the triples in Fig. 3c are taken into account, patient *patient2015* would be classified as a `Patient2FlexGlenoJ`, because he has reported a VAS value of 0.0 (<3.0) and there exists in his current physiotherapy record a movement exploration of flexion of the glenohumeral joint where he achieved a ROM of 80° (which satisfies conditions of the class `MovExploFlexGJLessThan90`). Beware that the classification of the patient evolves alongside his evolution in the therapy: if after being in phase 2 and performing the exercises recommended for that phase the aforementioned ROM increases to 100° and the patient reports no pain when performing those exercises, the patient would no longer be classified as a patient of phase 2, but as a patient of phase 3 (see definition for `Patient3FlexGlenoJ`).

Results for Intended Use 4

In the last intended use, the ontology is regarded as a means to identify which exercises are most suitable for a patient at some specific moment given all the information that it is known about him. Three cases are considered:

(1) *Recommended exercises due to classification in one phase of a protocol*: as each patient is classified in a phase of a protocol (intended use 3) the exercises that were selected for that phase (intended use 2) are recommended for the patient.

(2) *Recommended/Contraindicated exercises due to general physiotherapy knowledge*: General axioms about physiotherapy have been added to the ontology to represent knowledge such as "*People with a personal past history of dislocation of glenohumeral joint should not perform exercises that contain abduction movements with a ROM greater than 80°*".

(3) *Recommended/contraindicated exercises for a specific patient:* The physiotherapist can specify at any time that an exercise is recommended/contraindicated for a specific patient. For example "*patient2015 should not perform exercises that contain extension movements*".

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Object properties `recommended` and `contraindicated` have been created to represent these facts. Moreover, when case (3) applies, a new class is defined as the set that only contains the current patient (Fig. 6).

```
                Patient3FlexGlenoJ ⊑ ∃recommended.Exer3FlexGlenoJ                                (1)

  PatientPastDislocationLeftGlenoJ ≡ Patient ⊓ ∃hasRecord.(PhysiotherapyRecord ⊓                (2)
                                     ∃hasAnswer.(CA1.7⊓
                                     ∃hasPastHistory.(DislocationOfLeftGlenoJ ⊓
                                     ∃hasPatient.Self)))
  PatientPastDislocationLeftGlenoJ ⊑ ∃contraindicated.ExerAbduLeftGlenoJGreaterThan80

 PatientPastDislocationRightGlenoJ ≡ Patient ⊓ ∃hasRecord.(PhysiotherapyRecord ⊓
                                     ∃hasAnswer.(CA1.7⊓
                                     ∃hasPastHistory.(DislocationOfRightGlenoJ ⊓
                                     ∃hasPatient.Self)))
 PatientPastDislocationRightGlenoJ ⊑ ∃contraindicated.ExerAbduRightGlenoJGreaterThan80

                       Patient2015 ≡ {patient2015}                                               (3)
                       Patient2015 ⊑ ∃contraindicated.ExerExtension
                     ExerExtension ≡ Exercise ⊓ ∃hasInitialMovement.(MovExtension ⊔ ∃hasFurtherMovement.MovExtension)
                      MovExtension ≡ Movement ⊓ ∃hasComponent.(Submovement ⊓ ∃hasMovementType.Extension)
```

Fig. 6 Results for intended use 4.

The most suitable exercises for a patient *p* will be represented by the named classes X_p such that $X_p \in Q1$ but $X_p \notin Q2$ where

$Q1 = \{ Z \mid Z \sqsubseteq Y \wedge p \in C \wedge C \sqsubseteq \exists recommended.Y \}$

$Q2 = \{ Z \mid Z \sqsubseteq Y \wedge p \in C \wedge C \sqsubseteq \exists contraindicated.Y \}$

being C and Y also named classes.

DISCUSSION

It is of no doubt that information technologies are playing a relevant role in the research and improvement of the healthcare domain[30-33]. In the field of patient physical recovery, software for physiotherapists to manage rehabilitation processes has been available as commercial products for some years[34,35]. These systems represent the transition from a paper-based storage to standardized electronic records, but while they have been specially focused on data recording and administrative purposes, they do not use techniques such as Clinical Decision Support (CDS)[36] that would allow them to deepen in the use of the data gathered for assisting physiotherapists in diagnosis, treatment definition and patient monitoring.

CDS systems have been implemented usually using artificial intelligent techniques. Considering the field of physiotherapy, for example, Gross et al.[37] use machine learning techniques to develop a CDS tool for selecting appropriate rehabilitation interventions for injured workers. Moreover, in Hawamdeh et al.[38] the resilient backpropagation artificial neural network algorithm is used to accurately predict the rehabilitation protocols prescribed by the physicians for patients with knee osteoarthritis. Finally, a CDS system based on a Bayesian belief network for musculoskeletal disorders of the shoulder is presented in [39].

However, to the best of our knowledge, only few papers address the problem from the point of view of semantic technologies. Button et al.[20] present TRAK, an ontology that models information for the rehabilitation of knee conditions. It aims to standardize knee rehabilitation terminology and integrate it with other relevant knowledge sources. Although we acknowledge the usefulness of TRAK, we feel that it does not take advantage of all the capabilities of that semantic technologies offer, especially with regard to reasoning, which would require greater detail in the definition of concepts. In [40] Dogmus et al. introduce REHABROBO-ONTO, an ontology to represent information about rehabilitation robots. This ontology helps in the process of selecting the right rehabilitation robots for a particular patient or a physical therapy, by means of a web interface. However, it differs from our solution in the fact that it does not integrate the description of the patient report and thus it is just a query tool.

None of the previous ontologies allow for a reasoning process that changes over time according to the patient's state and performance. *TrhOnt* has achieved this purpose by integrating the representation of the patient report, protocol treatments, exercises and evidence-based rehabilitation knowledge.

CONCLUSION

Semantic technologies have been widely used in several medical fields in order to facilitate the work of physicians. In this paper we have presented a new ontology for physiotherapists from two different perspectives. On the one hand, from the point of view of its creation, by showing how it has been created by integrating information from different resources: pre-existing ontologies, databases of movements, exercises and treatment protocols, experts' knowledge, patient records, etc. On the other hand, from the perspective of its usage and the relevant information that it provides for the physiotherapists via a reasoning process. This information includes recommended exercises, the current phase of a protocol in which a patient is, etc. That is, information that can improve rehabilitation processes.

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