Knowledge-Based Telerehabilitation Monitoring

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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.

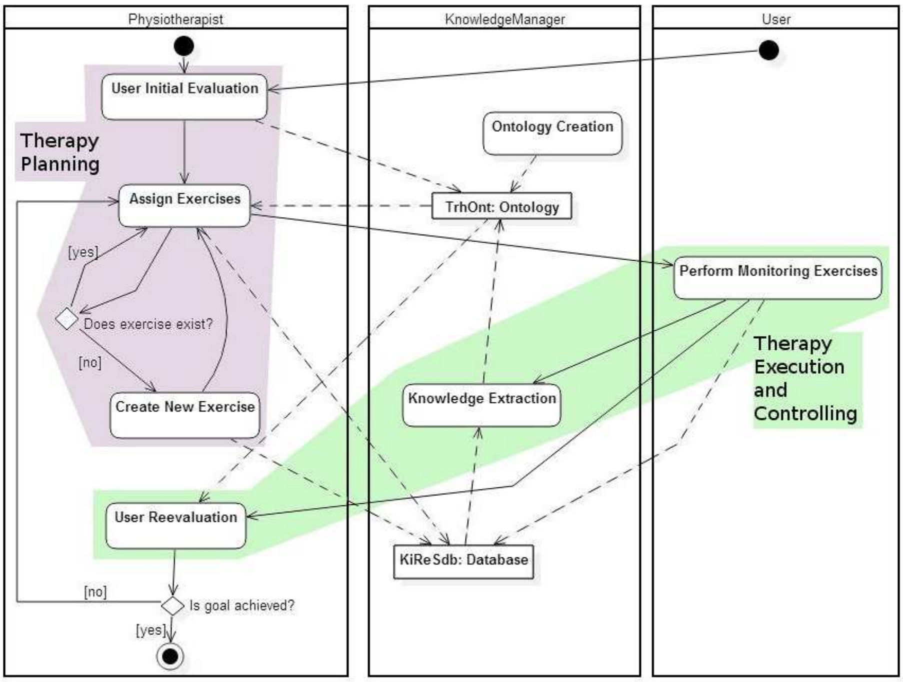

Fig. 1. KiReS activity diagram

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

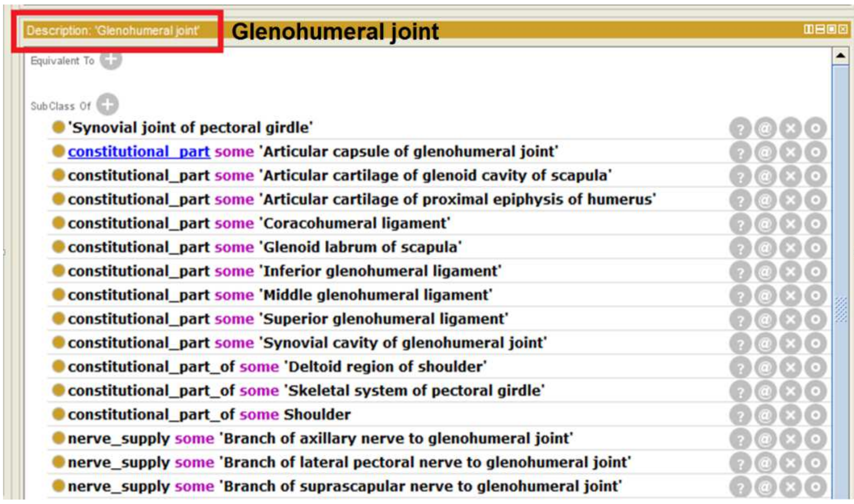

Fig. 2. Axioms about Glenohumeral Joint in Protégé

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.

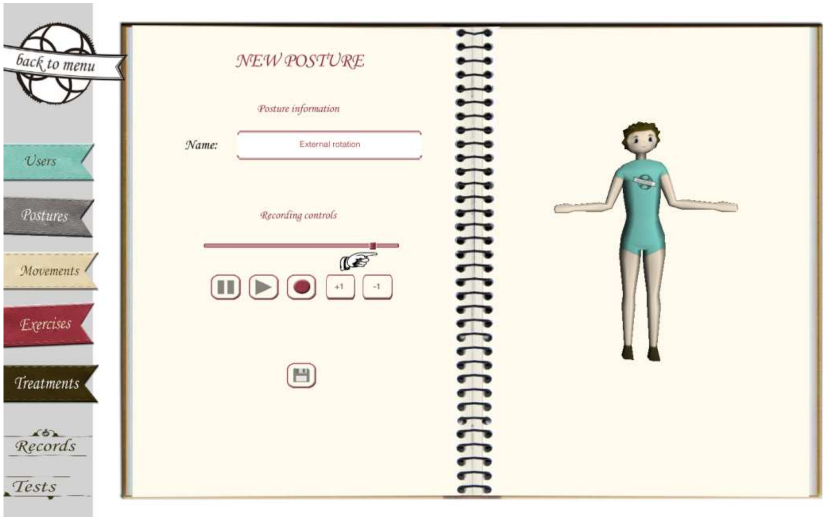

Fig. 3. Posture edition

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.

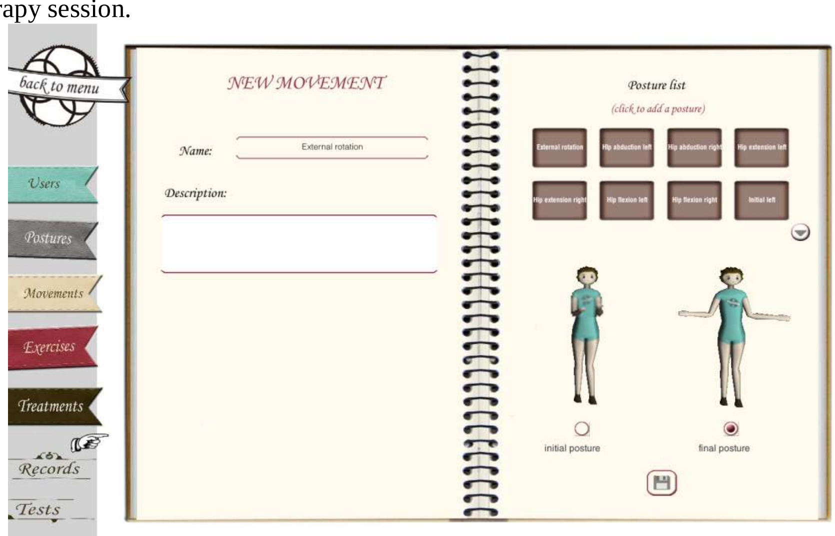

Fig. 4. Movement definition

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.

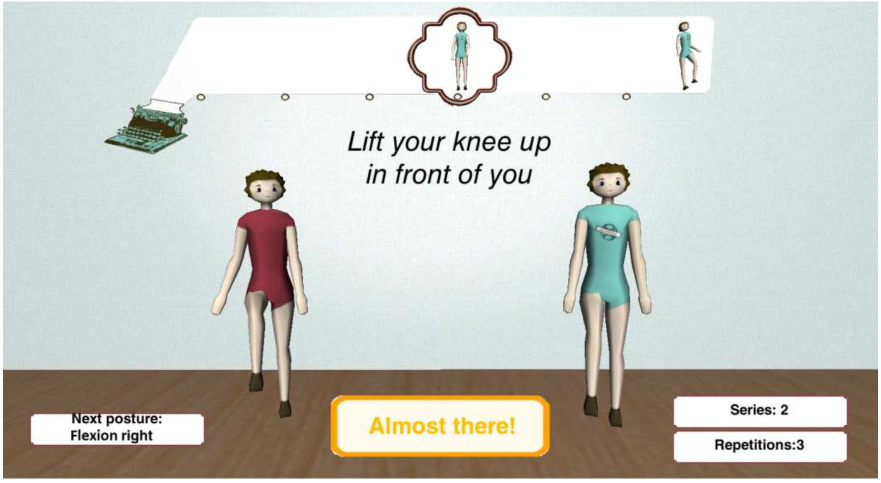

Fig. 5. User exercise interface

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.

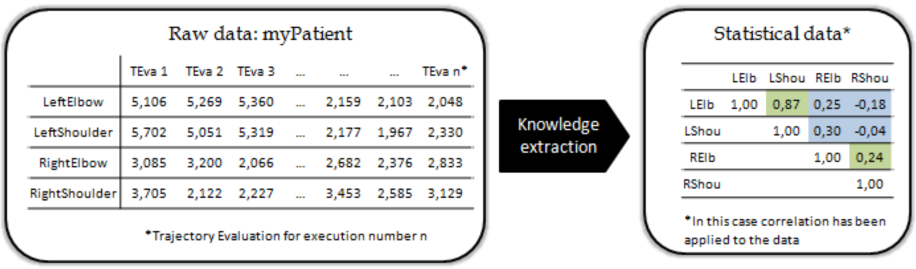

Fig. 6. Knowledge extraction example

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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