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Engineering Rehabilitation: Blending two Tool-supported Approaches to Close the Loop from Tasks-based Rehabilitation to Exercises and Back Again

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Abstract – Post-stroke or post-brain injuries rehabilitation is a long-term process defined by therapists and tuned to the specific damages and their consequences for each patient. This process requires the definition of well-defined multiple exercises to be performed multiple times by each patient over a long period of time. One of the key findings in the rehabilitation domain is that exercises should be tasks and goals oriented to increase functional independence, enhance development and prevent disability [24]. Patients performing the exercises must be carefully monitored to identify progress, possible regression and prevent damages due to the inadequate performance of the exercises. The SIVIRE tool [20] provides interactive graphical feedback to patients about the performance of their exercises and deviations from nominal, planned practice but fails at providing high-level descriptions of exercises and at connecting them to high-level rehabilitation goals (e.g. gain autonomy in cleaning a room). The HAMSTERS-XLE tool [16] provides a tuneable editor and a simulator to describe goals and task models including low-level tasks covering perception of the various senses, cognition and motoric actions. This paper presents the integration of these two tools and the benefits it brings both to the patients and to the therapists. The resulting tool and its engineering are presented in detail highlighting some generic integration mechanisms. On a case study, we show how exercises can be defined in HAMSTERS-XLE, transferred to SIVRE for fine tuning, monitored by SIVRE during the multiple practices of the patient and transferred back again to HAMSTERS-XLE to monitor progress, identify issues with the exercises and provide therapists with goal and task-based data about patients' evolutions.

CCS Concepts: • **Human computer interaction (HCI) → HCI theory, concepts and models • Software and its engineering → Integrated and visual development environments.**

Additional Key Words and Phrases: **Task modelling, Continuous monitoring, Rehabilitation, Post-stroke, Exercises**

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1 INTRODUCTION

According to the World Stroke Organization in the Global Stroke Factsheet released in 2022 [28], lifetime risk of developing a stroke has increased by 50% over the last 17 years and now, 1 in 4 people is estimated to have a stroke in their lifetime. A stroke may cause several types of impairments. These impairments can be motor such as hemiplegia (paralysis on one side of the body). They can be cognitive such as aphasia (inability to comprehend or formulate language), hemineglect (failure to be aware of items to one side of the vision space) or apraxia (inability to perform familiar

movements on command). They can also be perceptive such as sensory disorders or micropsia (objects perceived to be smaller than they actually are). In the days following the stroke (from 3 to 10 days usually), the neurologists provide care to stabilize the patients' state and to avoid complications. Once the patient's state is stabilized, if the patient still has severe impairments, a team of specialists (occupational therapist, physical therapist, cognitive therapist...) in stroke rehabilitation handles a rehabilitation program for the patient.

The aim of a stroke rehabilitation program is to reduce the after-effects of stroke and restore the capacity of stroke victims. Post-stroke or post-brain injuries rehabilitation is a long-term process defined by therapists and tuned to the specific damages and their consequences for each patient. This process requires the definition of well-defined multiple exercises to be performed multiple times by each patient over a long period of time. One of the key findings in the rehabilitation domain is that exercises should be tasks and goals oriented to increase functional independence, enhance development and prevent disability [24]. Patients performing the exercises must be carefully monitored to identify progress, possible regression and prevent damages due to the inadequate performance of the exercises. Several technologies and tools have been proposed to assist rehabilitation team in performing exercises. However, the benefits of these technologies and tools are limited to a particular task and body part, and does not take into account all of the user's tasks for the rehabilitation program. To overcome this limitation, we integrated two types of tool-supported approaches in a goal-based rehabilitation process. The first tool-supported approach is based on task models and enables to refine rehabilitation goals in tasks and exercises that exhaustively cover the needs of the rehabilitation program. The second tool-supported approach focuses on a specific type of movement-based task and relies on posture to describe rehabilitation movements.

Next section highlights the importance of goal and task-based rehabilitation programs, as well as points out the issues currently faced when implementing this type of rehabilitation program. Section 3 presents each of the tool-supported approaches integrated in a goal-based rehabilitation process, as well as their integration to overcome the issues currently faced when implementing goal-based rehabilitation programs. Section 4 presents the results of the implementation of the integrated approach for a rehabilitation exercise named the shape sorter drum task. Section 5 summarizes the benefits of the proposed integrated approach. Section 6 presents the related work on engineering contributions for task-based rehabilitation. Section 8 concludes the paper.

2 GOAL AND TASK BASED REHABILITATION

To set goals with post-stroke patients, to propose them exercises (composed of several tasks) and to monitor their progress are the main missions of rehabilitation practitioners [24], which work within a coordinated multidisciplinary team [27]. Setting goals increases the patients' behaviour change and help them reducing the limitations they face after stroke. Such approach is named goal directed rehabilitation [1].

2.1 Goal directed rehabilitation process

Figure 1 presents an overview of the goal directed rehabilitation process [3]. From the initial patient's status, the rehabilitation team and the patient propose and negotiate high-level goals. Examples of high-level goals are: "be able to prepare oneself a simple meal", "be able to read the newspaper", "be able to put away the laundry", "be able to have a walk-in front of my home" ... The rehabilitation team then refine these goals in specific sub-goals that will help patients to acquire the skills and knowledge required to reach the high-level goals.

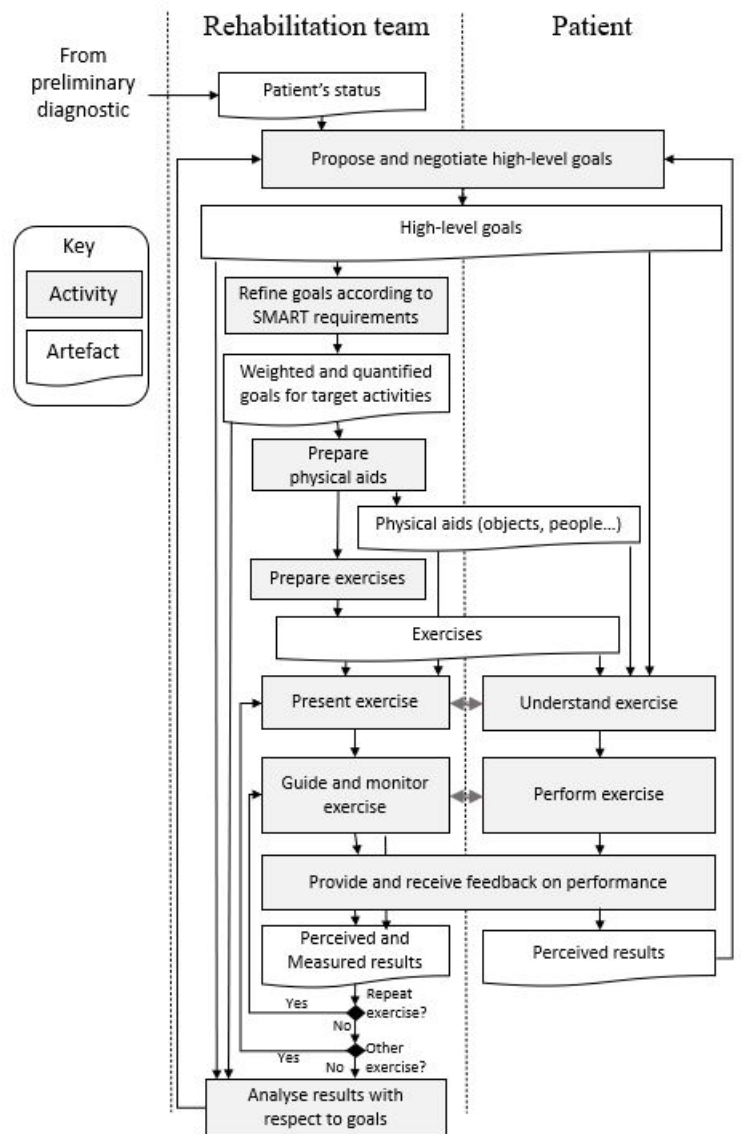


Figure 1. Overview of the goal directed rehabilitation process (from Wade [1] and Bovend'Eert et al. [3])

There are existing guidelines that support the refinement of the high-level goals. For example, the SMART method [1] aims to refine goals in tasks for which the outcome of execution can be quantified. The aim of this method is to support the individualization of the rehabilitation program, to allow explicit assessment of goal achievement and to be flexible enough to cover most situations. For example, the high-level goal “be able to prepare oneself a simple meal” is refined into quantified goals and an example of one of these is “grab one plate from the shelf two times a day”. The refined goals may be weighted depending on their importance relatively to the patient’s needs and towards achieving the high-level goal. From the refined goals, the rehabilitation team prepares a set of exercises to train and enable the patient to reach the refined goals after a couple of days. Then, for each exercise, a practitioner from the rehabilitation team presents the exercise to the

patient and ensures the patient understands. The patient performs the exercise while being monitored by the practitioner. At the end of the exercise, the patient receives feedback on the performed exercise. Once all of the exercises are performed, the rehabilitation team analyses the results in relation to the high-level and refined goals.

2.2 Example of the Shape Sorter Drum Task (SSDT)

The Shape Sorter Drum Task (SSDT) is used to measure movement performance with a substantial amount of visual and somatosensory requirements. For this task, the patients are required to take objects from a standard position and to put them into a drum with their more affected hand (illustration in Figure 2). This task is very interesting because it trains perceptive (perceive the shapes, perceive the variation of luminous intensity as holes are darker), cognitive (recognize shapes) and motor skills (move upper limb joints). This exercise can help patients to train to recognize circle shaped objects as well as to train upper limb motor capacities. In return, this training supports to reach the refined goal “grab one plate from the shelf two times a day”, which is itself required to reach the high-level goal “be able to prepare oneself a simple meal”.



Figure 2. Picture of a patient performing the Shape Sorter Drum Task (from [25])

2.3 Specific issues of goal and task-based rehabilitation approaches

Goal and task-based rehabilitation approaches have proven successful because they focus on patients' concerns and help to motivate them [24]. The quality and successful implementation of the rehabilitation program depends on the analysis of the patient's results in relation to goals and tasks. We thus identified the following limitations and issues remaining to overcome:

- Neither goal directed nor task-based software applications explicitly support rehabilitation teams.
- There is few computer-based support to take into account the huge quantity of data to be managed for each patient: a lot of goals, refined goals, tasks, exercises... These data change regularly, and patients' performance too.
- The coverage of the available data for the analysis and the adaptation of rehabilitation program both rely only on the human processing abilities of the rehabilitation team.
- Many rehabilitation exercises require the presence of the rehabilitator to tell the patient precisely where he or she is failing. These are very repetitive exercises that have to be performed a large number of times throughout the rehabilitation process [14]. However, rehabilitation teams have many patients to take care of and have limited time to share amongst them.

3 TOOL-SUPPORTED INTEGRATED APPROACH FOR GOAL AND TASK BASED REHABILITATION

User tasks and goals analysis and description is a cornerstone of User Centred Design (UCD) approaches [4], aiming to collect information from users about the work they are doing and the way they perform it. We integrated a task description-based approach that is generic and aim to cover all target goals and tasks with a specific body posture focused

approach that aim to train patients to perform body movements. Each of them is tool-supported. The HAMSTERS-XLE supports the task description based approach and the SIVIRE tool supports the body-posture focused approach.

3.1 Tool support for goal and task-based rehabilitation

Figure 3 present an overview of the main concepts illustrating the integration of the proposed integration, which are developed throughout section 3.

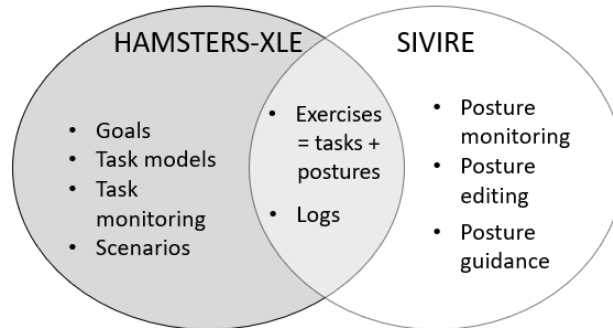


Figure 3. Main concepts illustrating the integration of HAMSTERS-XLE and SIVIRE

Although HAMSTERS-XLE is an agnostic tool and support the modelling of user tasks whatever the application domain, SIVIRE explicitly targets the rehabilitation of strokes patients.

3.1.1 HAMSTERS-XLE: A task modelling and simulation tool

The HAMSTERS-XLE software tool supports the editing and simulation of the execution of task models [16]. As user tasks may be numerous and complicated, HAMSTERS-XLE support to edit, refine and structure tasks models that embed a large number of tasks and provides elements of notation as well as tool support to split task models in several files, as well as to reuse part of them. The HAMSTERS-XLE software tool also supports the simulation of task models and the production of scenarios from the task models.

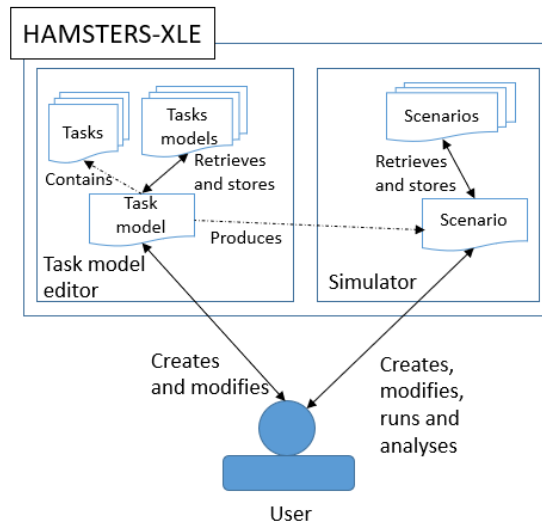


Figure 4. The high-level architecture of the HAMSTERS-XLE task modelling and simulation tool

Figure 4 presents the main elements composing the HAMSTERS-XLE tool: the task model editor and the task model simulator. The task model editor enables to edit and organise task models. From the task models produced, the task model simulator enables to execute task models step by step, presenting available tasks for execution and completing an execution scenario once the execution of a task is triggered.

For the purpose of describing rehabilitation exercises, we customized the HAMSTERS-XL notation as recommended in [16], and implemented new types of tasks and data using HAMSTERS-XLE capabilities. Figure 5 a) presents the movement task type which is a customized motor task and Figure 5 b) presents the customized data type “Range of motion”. They support the precise description of rehabilitation exercises (as illustrated in section 4.2).



Figure 5. Customized elements of notation created using HAMSTERS-XLE: a) the task type “movement” b) the notation for “Range of motion” parameter

3.1.2 SIVIRE: a tool suite for physical rehabilitation

SIVIRE is a system that accompanies the physical rehabilitation process of a patient [20]. It is composed of two main tools. On one hand, EVITE, a Virtual Exercise Routine Editor. On the other hand, REHABILITA, a tool for monitoring and guiding the rehabilitation process through Movement-Based Interaction to assist and monitor patients in their rehabilitation process, capturing and interpreting their movement. SIVIRE facilitates and enhances the work of the physiotherapist. The solution is non-invasive as patients do not need to wear any physical system attached to the body. The application is complemented by two additional modules: one for the management of patients and another one that collects statistics of operation, failures, times, and other data depending on the evolution of the patient. All of this is based on the concept of telecare. Figure 6 presents the high-level architecture of the SIVIRE tool suite.

The EVITE tool (represented as the box “EVITE” in Figure 6) enables the physiotherapist to design postures, exercises, and exercise routines. The main workspace in EVITE provides an outline of a human skeleton highlighting the joints that the specialist can work with. By simply clicking on a joint, it can be moved to form the appropriate posture in a 3D space. The posture can be visually examined in the three dimensions at the whim of the posture designer to identify the most appropriate posture. Once the postures have been designed, exercises, who are a sequence of postures that must be performed in a given order, are generated. The EVITE tool also enables the specialist to analyse data on the patient’s evolution and then to adapt and redefine exercises.

The postures and exercises are then stored in a distant server (represented as the “CLOUD” in Figure 6).

The REHABILITA tool aims to monitor and guide exercise through Movement-Based Interaction [10]. In particular, it enables to monitor and guide the patient during the performance of the exercise prepared using the EVITE tool and retrieved in the distant server. The REHABILITA tool provides visual indications to the patient about the exercises to be performed, how to perform them and the potential mistakes. With this proposal, it is the system that constantly warns the patient of any possible mistakes they may make in order to help them improve and makes it easier to repeat the exercises as many times as necessary. The REHABILITA tool displays to the patient the captured live image of her/him or a representation of the patient (in case the patient feels uncomfortable to see a self-live image). The exercises are performed in phases, and you can receive constant feedback in visual and auditory format. Once the exercises are completed, a set of statistics

(represented as “Logs” in Figure 6) is saved and sent to the distant server. The therapist can retrieve them later from EVITE, allowing him to analyse them and then change previously made exercises and their given postures accordingly to the patients’ progress.

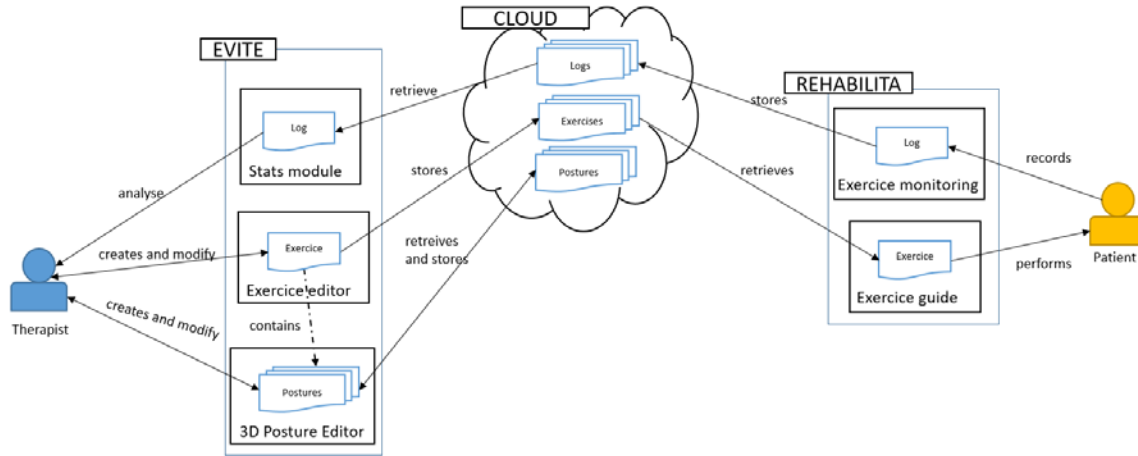


Figure 6. The high-level architecture of the SIVIRE tool suite

3.2 Process for closing the loop from goal and task-based rehabilitation to exercises and back again

As shown above, SIVIRE is a very specialized tool suite, designed around a very specific task: motor rehabilitation of a specific part of the body. This kind of approach permits to be very precise for these specific tasks but lacks to capture the “whole picture”.

On the other hand, HAMSTERS-XLE is a very generalist tool, designed to represent any kind of goal, task or interaction. This means that while it helps to represent any user tasks and supports the UCD design process, it does not provide support to describe and analyse specific rehabilitation tasks.

The integration of the very specialized approach with the generalist approach supports the application of a goal directed rehabilitation process, from the elicitation of high-level goals to the analysis of the patient performance when executing the detailed specific rehabilitation tasks which relates to high-level goals.

Figure 7 displays an enhanced version of the generic process previously described in Figure 1. The conception starts on defining the tasks needed for reaching the defined goal and enhancing them with relevant posture, allowing then to produce exercises that fulfil the goal and tasks.

The exercises can then be run using the co-execution of both tools, providing more details on the patient performance that are recorded in logs. From the logs, the task modelling tool annotates the related task models. Thanks to this annotated task model, the rehabilitation team has a more detailed description of goals, expected performance and reported performance, thus providing more details that can be used in the analyse phase allowing to further refine the goals or the exercises in the next iteration of the process.

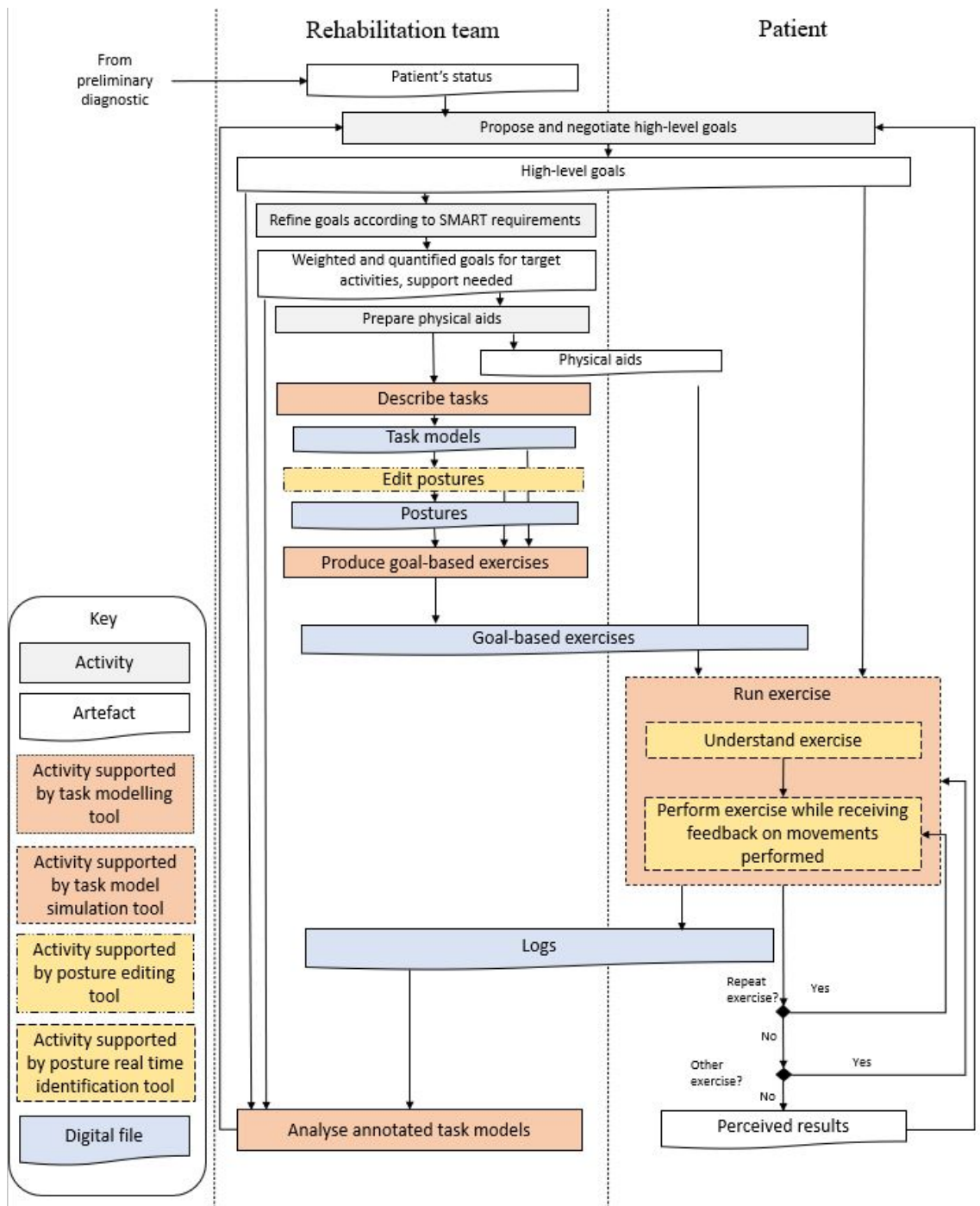


Figure 7. The goal and task-based rehabilitation process (including tool support)

3.3 Architecture of the integrated tools suite

Figure 8 presents the architecture of the integrated tool suite. It links together both tools described earlier. First, since the rehabilitation process is now goal based, related tasks are now created via the task model editor in HAMSTERS-XLE. These tasks can now be further enhanced with postures created by EVITE and stored in a distant server (CLOUD in Figure 8), allowing a more precise description of the tasks.

Exercises being now goal based, we no longer use EVITE editor for exercises but instead the simulator module HAMSTERS-XLE that will store the created goal-based exercises in a distant server. This module is called a simulator because it not only allows creation and modification of goal-based exercises, but can also re-execute them.

By retrieving distant exercises, this allows execution of exercises on both REHABILITA and HAMSTERS-XLE, as this kind of synergistic design has been proved to provide more benefits over asynchronous execution in critical interactive systems [18], providing feedback not only on the execution of the movement, but also on the execution of the goal as a whole.

Both tools store logs in the distant server, then can be later be retrieved by in HAMSTERS-XLE, allowing to replay both exercises in the task model for analysis purposes.

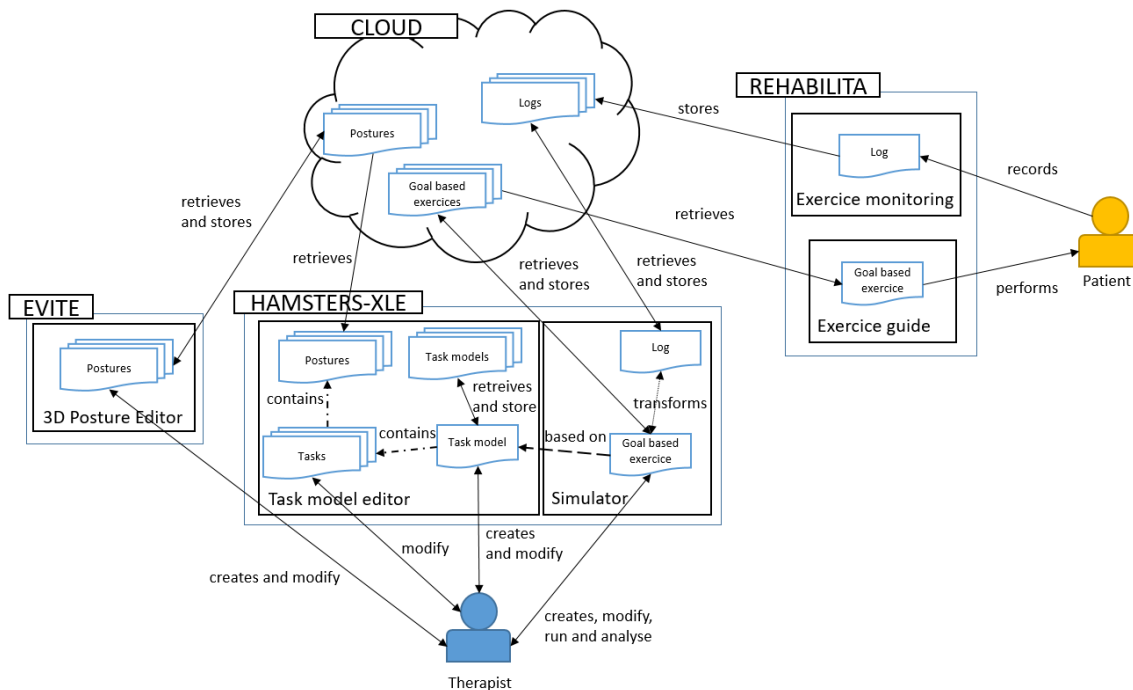


Figure 8. Architecture of the integrated parts of HAMSTERS-XLE and SIVIRE

4 THE SHAPE SORTER DRUM TASK CASE STUDY

As introduced in section 2.2, the shape sorter drum task can be used to train patients to recognize, for example, circle shaped objects as well as to train upper limb motor capacities. This training exercise supports to reach the refined goal

“grab one plate from the shelf two times a day”, which is itself required to reach the high-level goal “be able to prepare oneself a simple meal”.

In this section, we present the results of the preparation and implementation of the exercise “Sort shape in a given order” using the tool-supported integrated approach for goal and task-based rehabilitation.

4.1 Prepare physical aids

This exercise requires an electronic shape sorter drum that will support the monitoring of the tasks of the exercise, as well as provide visual cues and feedback to the patient. Figure 9 presents a schematic view from the top of the shape sorter drum. It is composed of four holes of different shapes, as well as of pairs coloured lights, each one being associated to a hole. Because of their unique shapes, the user cannot enter a piece in a wrong slot (like inserting a square piece in the round piece). However, they can insert a piece in an incorrect order (for example inserting square shape when round shape was required). At the beginning of the exercise, the lights are off. The patient is in front of a monitor that will display what piece should be inserted. Once a piece has been inserted in a hole, one of the lights corresponding to the hole turns on. If the right piece has been inserted in the corresponding hole, the green light turns on, else the red light turns on.

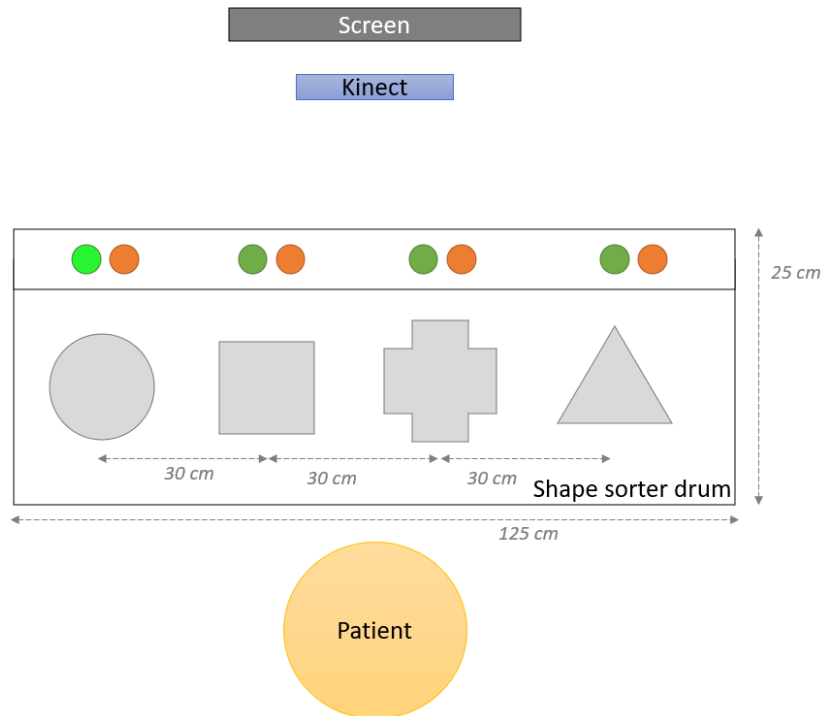


Figure 9. Schematic view from the top of the setup

Figure 10 presents the component diagram of the shape sorter drum (using UML component diagram [1] formalism). This diagram presents the different electronic and software parts of the shape sorter drum. In addition to lights (identified as “LED” components in the diagram), the shape sorter drum also embeds sensors for each hole, in order to detect what piece has falling down in a hole. The shape sorter drum is connected to computer (labelled “System”) that embeds HAMSTERS-XLE and SIVIRE software. Figure 11 presents a picture of the main components of the technical setup.

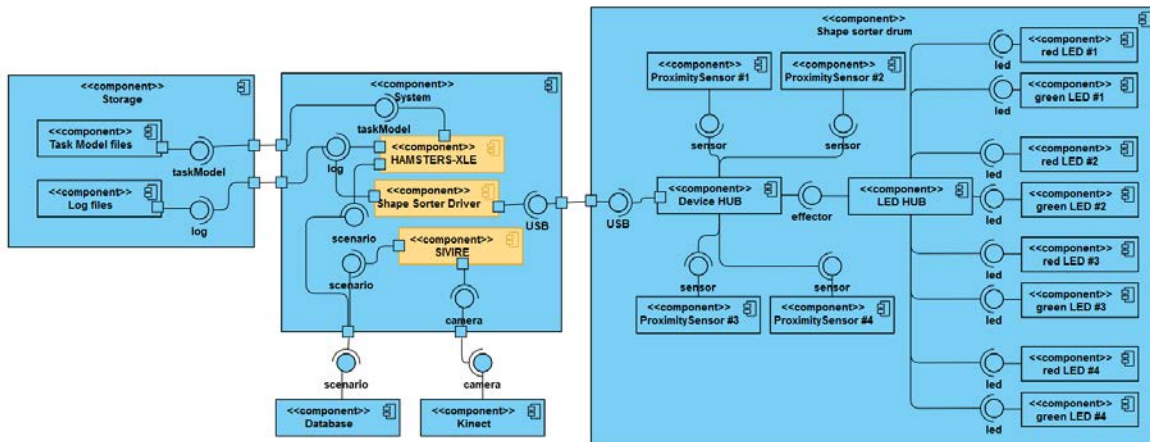


Figure 10. Main components supporting the integrated approach for the Shape Sorter Drum Task

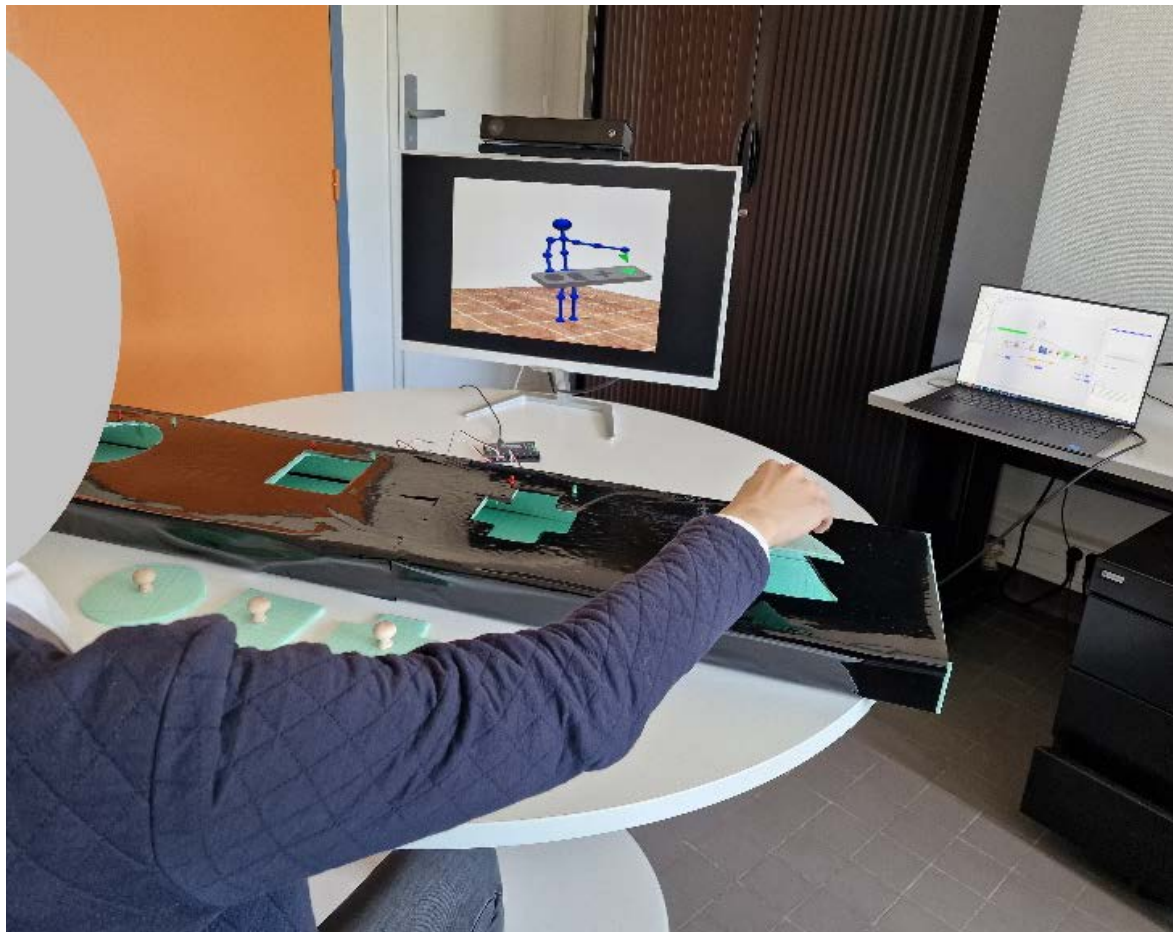


Figure 11. Picture of the main components supporting the integrated approach for the Shape Sorter Drum Task

4.2 Describe tasks

Figure 12 presents the main patient tasks to “Sort shapes in a given order” (main goal represented at the top of the task model and labelled “Sort shapes in a given order”). The patient performs the shape sorting tasks (abstract user task labelled “Sort shape”) while (concurrent temporal ordering operator ‘|||’) the HAMSTERS-XLE and SIVIRE tools guide and monitor the patient (abstract system task labelled “Monitor and guide patient”). The sort shape abstract user task decomposes in a sequence of abstract user tasks required to be performed to sort on shape: understand the target shape, look for adequate hole and piece (in an order independent way, described with the order independence ‘|=|’ temporal ordering operator), reach piece, grab piece, lift arm, move piece over the hole (which we refine and study in details in the next paragraphs) and drop the piece. Several of these tasks require input and output devices (speaker, shape sorter drum, lights, screen, Kinect), as well as physical objects (set of pieces, piece).

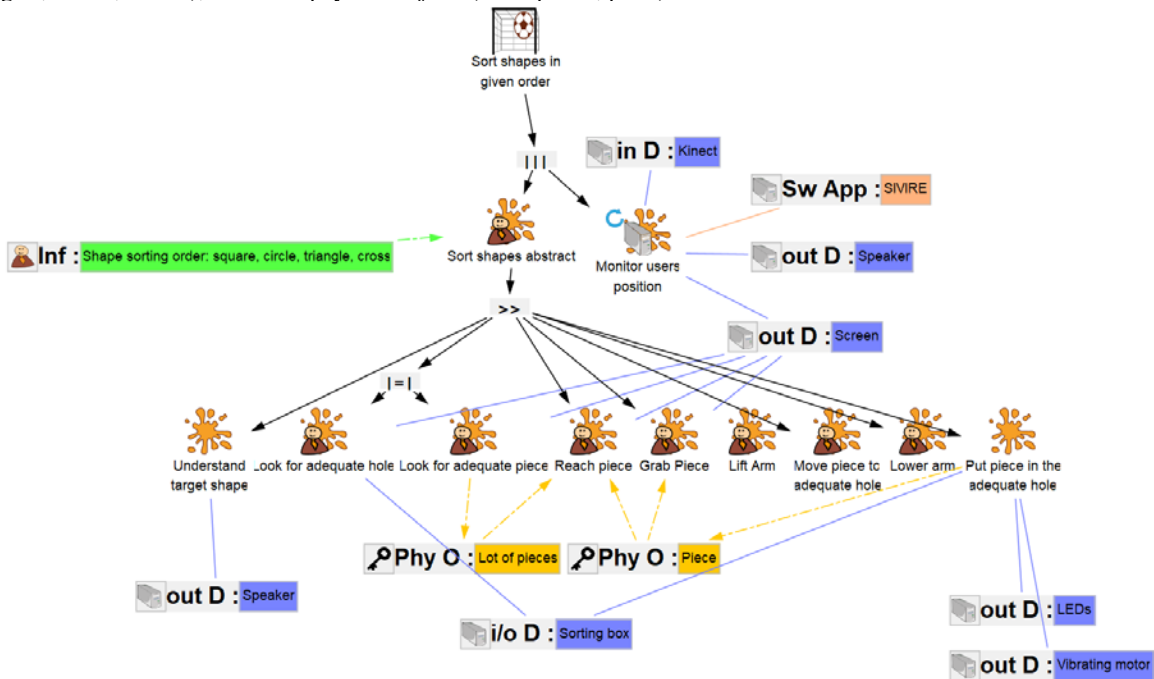


Figure 12. Main user tasks for performing the exercise “Sort shape in a given order”

These main tasks are then refined to identify low-level tasks (cognitive, perceptive, motor). Figure 13 presents an extract of the refined task model for the abstract task “Move piece over the hole”. The patient has to reach for box iteratively (user task labelled “Reach for box”) until (temporal ordering operator disable “[>]”) analysing that posture is reached (cognitive analysis task labelled “Feel posture is reached”) and deciding to stop movement (cognitive decision task “Decide to stop the movement”). At any time, the patient may interrupt the reach for box task (temporal ordering operator “[|>]”) to decide to check posture on the screen. Checking posture on the screen is the sequence (temporal ordering operator sequence “>>”) of the following tasks: decide to check posture (cognitive decision task labelled “Decide to check posture”), move the head (motor task labelled “Move head”) until (temporal ordering operator disable “[>]”) seeing the screen (perceptive sight task labelled “See screen”) and deciding to stop movement (cognitive decision task labelled “Decide to stop movement”), then

check posture (perceptive sight task labelled “Check posture”). The cognitive analysis task “Analyse posture is reached” required the information labelled “Target posture” and “current posture”, which are being updated by the perceptive sight task “Check posture”.

The motor tasks are refined to identify and describe the movements of the different part of the body that the patient will train. The motor task “Reach for box” decomposes in the concurrent execution (temporal ordering operator ‘|||’) of the following movements of the right shoulder: lateral rotation, which should be performed with an angle between 40° and 50°, and flexion, which should be performed with an angle inferior to 5°. The left rotation of the thoracolumbar spine, as well as of the cervical spine may happen but should not exceed 5°. The motor task “Move head” decomposes in a choice of flexion or extension of the cervical spine, and both of them should not execute beyond 5° (as the screen stands in front of the patient behind the shape sorter drum).

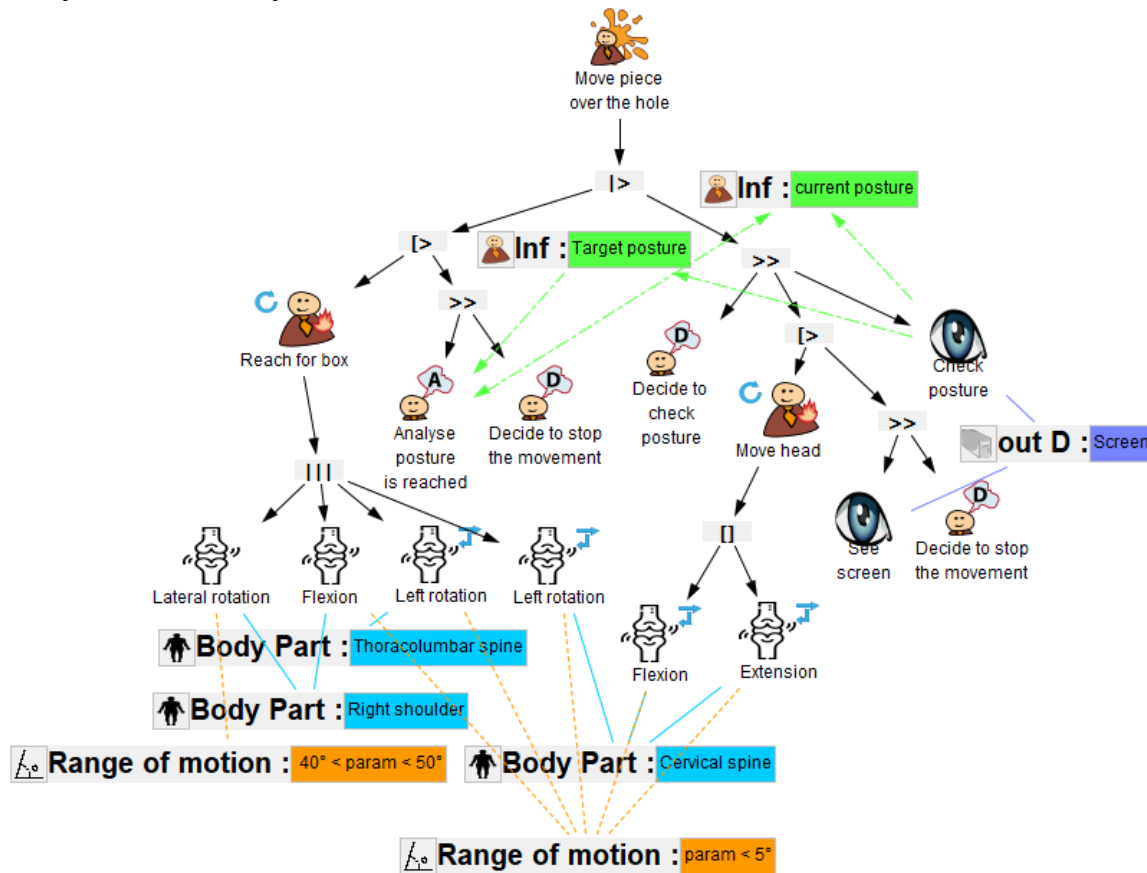


Figure 13. Task model of the sub-goal “Move piece over the hole”

4.3 Edit postures

User tasks in task models match postures which are edited using the EVITE tool of the SIVIRE tool suite. Figure 14 presents a subset of the postures to be hold by the patient during the exercise. In particular, we present the postures that

matches the presented task models. Figure 14 a), b), c) respectively presents the posture that has to be achieved at the end of the abstract user task “Reach piece”, “Lift arm” and “Move piece over the hole”.

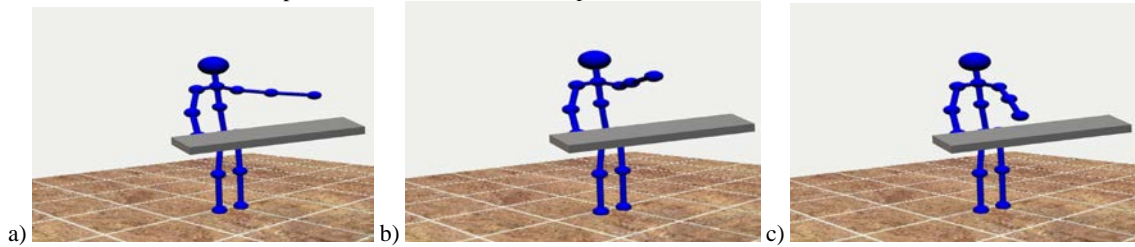


Figure 14. Edited postures to be achieved at the end of the abstract tasks a) “Reach piece” b) “Lift arm” c) “Move piece over the hole”

4.4 Produce goal-based exercises

Figure 15 presents an extract of the goal-based exercise “Sort shapes in a given order”. The sequence of tasks matches the abstract user task “Move piece over the hole”. It has been produced from task models using HAMSTERS-XLE. The body movements have been filtered out as they are detailed descriptions that are not shown to the patient.









-  -12 - Reach for box
-  -13 - Decide to check posture
-  -14 - Move head
-  -15 - See screen
-  -16 - Check posture
-  -17 - Reach for box
-  -18 - Feel posture is reached
-  -19 - Decide to stop the movement

Figure 15. Extract of the goal-based exercise for the abstract user task “Move piece over the hole”

4.5 Run exercise

The exercise running on HAMSTERS and SIVIRE guides the patient using in a synchronised way the sequence of tasks and the sequence of postures. Figure 16 presents the timeline view of the sequence of tasks to be performed, with the focus set on the current task to be performed by the patient. In the figure, the focus is set on task “Reach for box”, for which displayed posture has to be performed.

4.6 Analyse annotated task models

We use task models that are annotated with the information collected during the practice of exercises. These annotated task models enable to analyse the patient’s performance, and in particular to compare each movement performed with the movements that should have been performed during the exercise.

The logs produced during the training session contain information about the sequence of performed tasks (through HAMSTERS-XLE simulator), the patient body movements (through SIVIRE and its associated Kinect), as well as about the events of piece insertion in the shape sorter drum box. This information enables to produce annotated task models to support the analysis of patient performance and issues. Figure 17 presents the annotated task model for the abstract user task “Move piece over the hole”. Tasks for which issues were sensed and logged are highlighted in dark red. In the presented example, some movements tasks caused issues but the sub-goal “Move piece over the hole” was reached for each tentative.

The movement task “Left rotation” of the thoracolumbar spine is highlighted with a transparent dark red colour, as well as the range of motion constraint description “Range of motion: param < 5°”. When moving the mouse cursor on the range of motion constraint data, a tool tip panel displays listing the values measured at each iteration of the task during the training exercise. Starting from the third occurrence of the task, the left rotation of the thoracolumbar spine exceeded the expected value, meaning that the patient bent over too much instead of flexing the right shoulder.

When moving the mouse cursor on the range of motion constraint to the highlighted range of motion constraint description “Range of motion: 40° < param < 50°” connected to the “Lateral rotation” movement task, a tool tip panel displays (in Figure 18) listing the values measured at each iteration of the task during training exercise.

The range of motion description represent the expected value to ensure that the movement is valid. Starting from the third occurrence of the task, the lateral rotation range of motion was lower than expected, meaning that the patient did not manage to rotate enough the right shoulder. The “Move piece over the hole” was reached for each tentative and this result confirms that for the two last presented iterations of the task, the patient did not manage to flex the shoulder and compensated too much by bending over the thoracolumbar spine. Such issue could have been cause by fatigue or pain.

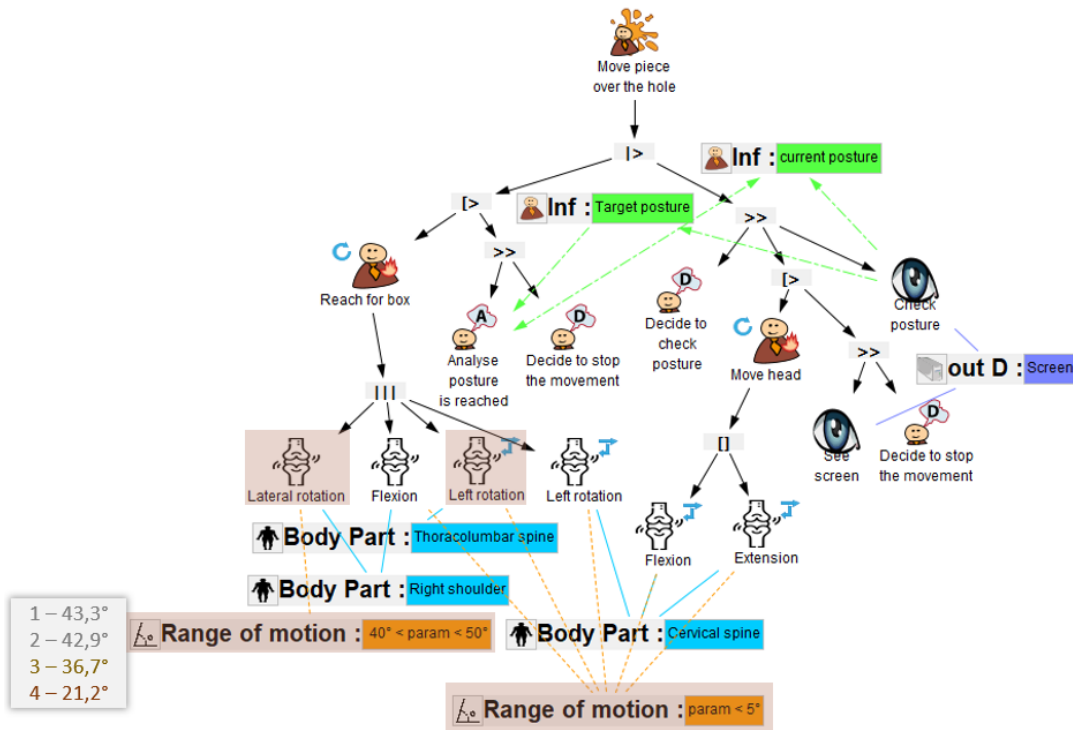


Figure 18. Task model of the sub-goal “Move piece over the hole” annotated with results of lateral rotation of the right shoulder

5 BENEFITS OF THE INTEGRATED APPROACH

The integrated approach takes advantage of the benefits of both the task-model-based approach (implemented using HAMSTERS-XLE) and of the SIVIRE movement training tool. Besides, their integration brings additional benefits which are summarized in Table 1.

The task-model based approach (using HAMSTERS-XLE) is goal-based and as such, matches the needs for the implementation of efficient rehabilitation programs [24]. The expressive power of HAMSTERS-XLE enables exhaustive representation of goals and tasks, of all of the desired temporal orderings of these tasks, and of the objects used for the performance of the tasks (in our case, physical aids as the ones in the case study). HAMSTERS-XLE generates a list of scenarios covering in an exhaustive manner these task models, which are the backbones of the rehabilitation exercises. The analysis of the performance of these scenarios makes it possible to verify if the rehabilitation goals are reach partially on in their entirety. Finally, the simulator of task models is used to guide patients indicating the next task to be performed for motor tasks (as SIVIRE) but also for cognitive and perceptive tasks. The movement training tool approach (using SIVIRE) enables to focus on the specific type of motor tasks, to provide precise guidance by showing how to perform the task, and to precisely measure how the patient has performed each motor task. Thanks to the precise guidance provided in an autonomous manner by the tool, it enables patients to perform rehabilitation tasks even without the therapist.

Table 1. Summary of the benefits of integrating a task-model based tool with a training tool for a specific type of task

Benefit	Task-model-based approach (HAMSTERS-XLE)	Movement-training-tool-based approach (SIVIRE)	Integrated approach
Goal-based approach	✓		✓
Exhaustive representation of goals and tasks	✓		✓
Exhaustive representation of all possible temporal orderings	✓		✓
Exhaustive representation of physical aids (objects, devices, software...)	✓		✓
Generation of exhaustive sets of exercises	✓		✓
Verification that exercises tasks match rehabilitation goals	✓		✓
Guidance by indicating the next task for all types of tasks	✓		✓
Specific task-based approach		✓	✓
Guidance by showing how to perform a task (for one type of task: perform posture)		✓	✓
Measure of the outcome of the performance of one type of task		✓	✓
Patient can train on a specific type of task even if therapist is not available		✓	✓
Verification of compatibility between rehabilitation goals and training tasks			✓
Synergistic guidance during training session (indicating and showing)			✓
Explicit description of data flows (goals, tasks, exercises, aids, measures...) used throughout the rehabilitation program			✓
Traceability between the results of training sessions and rehabilitation goals and tasks			✓

The careful integration presented in previous sections, makes it possible to keep all the benefits brought by each approach. The integration of the approaches brings multiple additional benefits. It enables verifying the compatibility between rehabilitation goals and the set of tasks in the exercises, and it provides a parallel guidance for movements (when needed) jointly with other non-motor tasks. This supports patients in identifying which tasks remain to be performed to

reach the rehabilitation goals, as well as graphical feedback on how to perform motor task in a specific movement-based part of the exercise. Merging the two types of feedbacks together is key for rehabilitation and is beyond current research and practice in rehabilitation. The integration of both approaches also makes explicit the data flow (information and knowledge) and the task elements (goals, tasks, exercises, measures, objects/aids...) throughout the rehabilitation exercises, and enables to connect the results of the rehabilitation exercises with the rehabilitation program goals and tasks. This makes it possible to assess the impact of the objects/aids used and to modify them when not adequate. Again this integration of objects, tasks and movements is unique.

6 RELATED WORK

Engineering tools for stroke rehabilitation were proposed to support rehabilitation specialists in conducting the recovery of their patients. These training systems automate specific training tasks previously directed by rehabilitation experts. They support patient guidance through selected recovery exercises for motor, proprioceptive, sensory, cognitive, sensory and cognitive abilities. Such training systems have several advantages. They can help rehabilitation specialists to manage more patients when practicing their exercises, either in presence or remotely. This makes it possible to support patients to do parts of the program at home.

6.1 Engineering contributions on post-stroke training tools mainly focus on specific body parts

In particular, they focus on specific impairments and specific movements. Patton et al. [19] focused on arm movements and highlighted the feasibility and relevance of using robotic training forces that monitor the patient ability to adapt arm movement. Meng et al. [17] focused on forearm movements and highlighted the feasibility and relevance of using an exoskeleton that enables patients to reach a 135° range of motion for the forearm. Furthermore, robotic devices are widely represented in the literature because they provide several benefits. They automate therapy procedure [9] and allow producing a large range of forces and motions for training [29], delivering measurable force [1] and intensity [26]. However, the contributions respectively focus on specific movements of specific body parts. Beyond robotics, other technologies support rehabilitation. Duff et al. [5] demonstrated the potential benefits of using an adaptive mixed-reality training system for arm training. Laver et al. [15] studied the effectiveness of a virtual reality training system for recovery of upper limb functions and activities of daily life and highlighted that it may be beneficial when used conjunctly with exercises that do not require devices. These approaches to the design, development and implementation of post-stroke training systems are necessary because each type of problem caused by a stroke requires the development and validation of a precise, adapted and safe response. However, the benefits of these systems are limited to the functionality or component that support a particular recovery objective and does not take into account all of the user's tasks for the rehabilitation program, which must be diverse and result from the combination of several types of exercises, as recommended by the World Health Organization [27].

6.2 Engineering contributions on post-stroke training tools respectively mainly focus on specific tasks

Technologies to support specialists in preparing and implementing the rehabilitation programs exist. They support different specialists' tasks: predict rehabilitation time, prepare training sessions, perform training session, analyse results of training sessions. Gu et al. [11] proposed a machine learning technique to support specialists by predicting individualized rehabilitation outcome, but it is limited to a specific disease (aphasia). RehaCom commercial desktop application [12] provides support to plan and perform cognitive rehabilitation exercises for several patients, but it is limited to a subset of cognitive exercises and that the specialists cannot customize. Plata et al. [21] proposed an interactive application for

physical therapists to monitor training exercises based on postures repetition but it focuses on patient positions only. ScienceSoft [22] proposes a commercial HW/SW Virtual Reality training platform with a library of training exercises and a progress tracking feature, but it is limited to virtual reality exercises. Khan et al. [13] demonstrated the feasibility of comparing patients' training exercises output data with a baseline using activity recognition, but it has been validated for dexterity training for apprentice surgeons, which are user profiles that are very different from stroke patients. To sum up, the existing contributions that support rehabilitation specialists' tasks are missing a global view on post-stroke rehabilitation, and in particular the goal and task-based aspect of the rehabilitation process. They thus fail in providing to the rehabilitation team a complete and consolidated view on the full set of goals and tasks that are defined, refined and worked on during the post-stroke rehabilitation program.

Recent work from Forbrig et al. [8] advocates for human-centred design of neurorehabilitation software. They propose to analyse rehabilitation team needs and context of use to drive the engineering of humanoid robots that would be supportive for rehabilitation training activities. They showed that task models support the modelling of collaboration between patients and the humanoid robot [6], as well as the development of an assistive humanoid robot [7].

7 LESSONS LEARNT ABOUT ENGINEERING TOOLS INTEGRATION

7.1 Related work on model-based tools integration

Limited research work has been focussing on tools integrations most of them being published at EICS conference series. As for the current paper, tools integration was performed when the tools were providing complementary perspectives and solving problems difficult to solve by the other tool. In [35] the CTTE task modelling and simulation tool was integrated with PetShop (interactive application model based on Petri nets) to provide a connected view on task descriptions with interactive application behaviour. This connection was made in an asynchronous manner through scenarios files produced by CTTE and used as input in PetShop following structuring proposed in [36]. In [32] the ICon (Input Configurator based on a data-flow model) tool was connected to PetShop; ICon providing low-level description of interaction techniques while Petshop was providing dialogue-level descriptions of application. In [18] the Amboss task model notation and tool were about to be integrated with PetShop with the goal of having both models used at runtime. Unfortunately, the incompatibility between Eclipse and NetBeans platform prevented this integration from being effective as reported by the authors. That paper however, provides a comprehensive analysis of the types of integration that can be performed (synchronous, asynchronous) as well as several communication protocols for integrating, at runtime, model-based tools. It also highlights the need for API and dedicated adapters (as presented in Figure 19). Finally, [38] presents the synergistic integration of the HAMSTERS task models and PetShop Petri net models at runtime offering system-model-driven and task-model-driven alternatives.

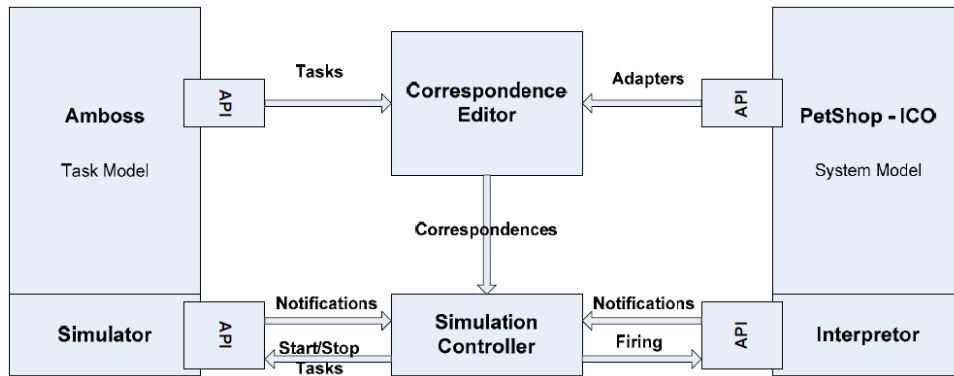


Figure 19. Connecting tools by means of API and adapters as proposed in [18] (Fig. 12 p 14)

Another integration approach has been aiming at integration model-based approaches with generic interactive applications (sometime called platforms) as flight simulators for instance. [37] is such an example where the former HAMSTERS tool is connected to a flight simulator to provide guidance to trainees. In this paper authors report that integration was made easy as the flight simulator was offering a dedicated API. Finally, integration has been proposed at the application level as in [30] where interactive application code has been augmented using and refining Java annotations for that purpose or in [31] where both formal models in PetShop and interactive application were integrated.

7.2 Integration of SIVIRE and HAMSTERS-XLE

Previous sections in the paper have demonstrated the benefits at the application domain level (rehabilitation) of integrating tools offering different views on the same world. HAMSTERS-XLE provides a goal and tasks high-level view on the rehabilitation exercises while SIVIRE provides a low-level movement-centred view on them.

As we integrate two tools, two different views have to be taken into account:

- A view centred on HAMSTERS-XLE simulation engine. In that case, this tool behaves as a client, using the other tool (SIVIRE) as a server providing services (movements definition, movement sensing and movement assessment), informing HAMSTERS about the outcome of the movement sensing with respect to the expected outcome.
- A view centred on SIVIRE sensing engine. In that case, this tool behaves as client using HAMSTERS-XLE as a server providing services about the execution of a scenario, the current task being performed, the next task to perform...

Both approaches require modifying the tools to make them reachable by other tools. In this paper we followed the first approach (HAMSTERS-XLE centered) as the tool has already been integrated with other ones such as PetShop formal modelling and execution tools [38]. Figure 20 presents the resulting API in HAMSTERS. This API makes it possible to use HAMSTERS as a server (see for instance the method `executeTask()`) or as client (see for instance method `connectToModel()`).

```

public interface HamstersTaskModelInstanceSimulator {

    public List<Task> getAvailableTasks();

    public List<ScenarioStep> getCurrentScenario();

    public List<Task> getCurrentScenarioTasks();

    public List<Task> getCurrentExecutedTasks();

    public void executeTask(Task task, List<String> list);

    public void gotoTask(Task task);

    public void resetSimulation();

    public void connectToModel(TaskModel model);

    public void addTaskToCurrentScenario(Task task, List<String> list,
                                           String string, Date date);

    public TaskModel getTaskModel();

    public boolean simulationComplete();

}

```

Figure 20. The HAMSTERS API for using HAMSTERS as a client as well as a server

This dual view on models' integration by means of editing and simulation tools provides a lot of freedom for exploiting tools developed by different teams. Having such integration perspectives from the very beginning of the design and development of a model-based tools would increase take-up-ability and provide systematic means to gather additional benefits, beyond the ones offered by each tool.

8 CONCLUSION AND PERSPECTIVES

The paper presented a solution to the important problem, in the rehabilitation domain, of providing tool support to the performance of goal-based rehabilitation exercises. We have used the HAMSTERS-XLE tool and its notation to describe the rehabilitation goals and their associated task-based exercises and enriched them with SIVIRE tools for postures definition and sensing. We have presented on a simple but largely used case study from the rehabilitation domain (the shape sorter drum task) how the integration of both approaches makes it possible to describe the exercise in an exhaustive manner the exercises including physical movements and body postures. To this end we have extended the HAMSTERS-XLE notation using the extension mechanisms embedded in the tool [16].

The paper has also presented the software and hardware architectures behind each tool including the specific elements (objects/aids) of the case study. This has demonstrated the generic natures of the tools and their tuneability for specific exercises involving different interactive technologies. This integration goes beyond state of the art in the rehabilitation domain both for researchers and practitioners.

The notation for describing exercises, the integration of SIVIRE and HAMSTERS-XLE simulator will provide many more benefits which go beyond the scope of this paper. For instance, we will be able to provide a library of exercises that can be used and assessed by practitioners in various contexts. The performance of the patients will be recorded and shared with the various practitioner to tune and adapt them to different types of patients. Standard exercises in that domain are very simple (usually limited to a short sequence of body movements) our approach allows the production of a set of

standard detailed goal-based rehabilitation exercises validated by the gathering of a large number of performance from patient.

At the engineering level, we have identified generic communication mechanisms based on adapters and APIs. More exercises involving more devices/aids are required to provide enough knowledge that would determine a generic multipurpose API.

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