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COMPUTER AIDED DISTRIBUTED POST-STROKE REHABILITATION ENVIRONMENT

Abstract *In this paper we present the results of a two-year study aimed at developing a full-fledged computer environment supporting post-stroke rehabilitation. The system was designed by a team of computer scientists, psychologists and physiotherapists. It adopts a holistic approach to rehabilitation. In order to extend the rehabilitation process, the applied methods include a remote rehabilitation stage which can be carried out of at the patient's home. The paper presents a distributed system architecture as well as results achieved by patients prior to and following a three-month therapy based on the presented system.*

Keywords remote rehabilitation, computer system, stroke

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1. Introduction

Stroke continues to be a major public health concern, with more than 790000 new cases per year in the USA [20]. In Italy (180000 cases/year, 80% first episodes, 20% recurrent) it is the 3rd leading cause of death (following cardiovascular disease and cancer) and the leading neurological cause of disability. Throughout the 27 EU countries the total annual cost of stroke is estimated at 27 billion (68.5% direct and 31.5% indirect costs) [6].

Brain tissue damage caused by stroke is organic in character and usually results in impairment of basic brain functions controlling important biological processes. Common disabilities that result from a stroke include: decreased attention span, selective attention deficit, decline in logical thinking, difficulty in performing planning and reasoning tasks, poor comprehension, synthesis and analysis skills, weakened short-term and long-term memory (verbal and/or visual) as well as speech disorders (e.g. aphasia or dysarthria). This leads to accumulation of symptoms which require therapeutic care. Post-stroke patients are often unable to fulfill their social or professional obligations. Difficulties in adapting to everyday life frequently produce mood disorders such as anxiety, irritability and apathy. Lack of self-reliance and reduced intellectual abilities often prevent patients from achieving their life goals and contribute to depression. Due to its complexity, this type of medical condition calls for a holistic and individualized approach to each patient.

Rehabilitation plays a vital role as it helps stroke victims recover their mental faculties – partly or fully – following brain injury. The choice of exercise plays a vital role, as does its correct and systematic performance. In addition, the duration of rehabilitation is very important. Modern information technologies enable remote, individualized outpatient rehabilitation, with proper supervision by physiotherapists or medical doctors. [4, 10, 17, 18, 21]

In this paper we present the results of a two-year project aimed at developing a full-fledged computing environment supporting post-stroke rehabilitation carried out at a rehabilitation centre and then continuing at the patient's home. The goal of the project was to validate the following hypotheses:

- Use of resources and tools provided by computer science enables the adoption of a holistic approach to rehabilitation of stroke patients, based on computerized support for concurrent stimulation of cognitive functions, motor skills and verbal faculties.
- Holistic approach to the rehabilitation of stroke patients yields better results than traditional methods which do not exploit IT tools. It is also better than computerized methods which do not adopt a holistic approach.

2. State of the art

Rehabilitation using virtual reality interfaces is a quickly evolving method of patient care, targeting – among others – victims of brain injuries such as stroke or multiple sclerosis [1, 22]. The use of virtual reality can play a role in setting up a scene which directly impacts the patient [5], and in allowing patients to train their cognitive and motor skills by interacting with the scene. Research [3] shows that this approach to rehabilitation of even severe brain damage is promising and can yield results which would be difficult to obtain using more traditional methods. A possible explanation of this phenomenon is reduced dependence on permanent care provided by trained rehabilitation specialists, and also the ability to perform exercises at one's own home, in a preferred environment.

Where direct interaction is needed, virtual reality support for patient rehabilitation usually assumes the form of a game. Such games range from simple puzzles or card games [2] where the patient controls virtual objects, to more complex physical activities in the form of a simulated sport [9, 27]. Due to patients' limitations, rehabilitation games are simple and focus on a single task, repeated many times at increasing difficulty levels.

3. Proposed rehabilitation method

In our approach, the post-stroke rehabilitation consists of four general stages:

- **Diagnostics.** The type and scope of disability is assessed on the basis of neurological examination and psychological tests.
- **Main rehabilitation stage.** The patient performs selected exercises over a period of approximately three months. During this period the set of exercises and their parameters are carefully adjusted to provide the best fit to the patient's needs and scope. Several sets, further referred to as training courses, can be defined for each patient.
- **Goal attainment scaling.** The patient undergoes diagnostic evaluation to assess progress.
- **Remote rehabilitation.** Selected patients may continue rehabilitation at home – an individualized computer application is provided, allowing doctors to monitor the patients' exercises over the Internet. The doctors may also introduce necessary changes in the performed tasks.

The design and implementation of the presented method involves:

- Preparing over twenty multi variant computer exercises.
- Automation of patient progress assessment.
- Boosting patients' interest in performing computer-aided exercises. For many patients this form of rehabilitation appears far more attractive than traditional methods.
- Introduction of remote rehabilitation where selected exercises can be performed outside the hospital (e.g. at home).
- Tools allowing the doctors to easily define new sets of exercises for individual patients, and to adjust their parameters.
- Tools to analyze patients' progress.

- Ability to perform holistic rehabilitation by executing exercises targeted at different disabilities in an alternating fashion as part of a single training course.
- Development of a programming environment (set of classes and methods) enabling programmers to extend the system by adding new exercises, designed and prepared by doctors.

4. Exercises – general concepts

The use of virtual reality is a fast evolving rehabilitation method for patients suffering from various types of diseases, including injuries and diseases of the brain, such as stroke or multiple sclerosis. During rehabilitation patients improve their cognitive and motor faculties by participating in virtual activities simulated by a computer. Such activities usually assume the form of games where the patient is a player. Research shows that the use of virtual reality yields better results than traditional rehabilitation methods [1,22]. One of the most important reasons why virtual reality is so effective is that it allows exercises to be performed at home, in an environment where the patient feels more comfortable than at a rehabilitation centre. It should also be noted that traditional rehabilitation requires constant supervision by skilled personnel, which prevents patients from performing rehabilitation tasks at home.

The exercises developed in the course of the presented research are not modifications of existing games (whose principal aim is to entertain) as these games are usually too complex and too difficult for patients to master, requiring substantial dexterity. Instead, games used during rehabilitation are simple, have limited graphics and focus on a specific task or on a small set of simple tasks. These tasks are repeated many times at increasing levels of difficulty.

The exercises are developed on the basis of guidelines introduced by psychologists and physiotherapists. Tasks to be performed by patients and visualization methods are designed in line with expert advice. For each exercise a parameter set is defined, including e.g. changes in scope, difficulty levels, number of repetitions, etc. Finally, evaluation methods are chosen (e.g. execution time, number of errors, precision or other criteria).

Given the above input data, programmers implement individual exercises. Implementation is followed by a verification round, where doctors analyze exercises and describe the necessary corrections which should be made by programmers. This cycle can be repeated many times – an exercise is only used during rehabilitation if its quality is deemed satisfactory. Owing to the use of object-oriented programming, adding new exercises is a straightforward task.

5. Groups of exercises

Some exercises help patients with aphasia while others improve manual dexterity, memorization or cognitive abilities. Most exercises target one specific disability, although there are also several exercises which deal with more than one disability. Sample exercises are shown in Figure 1.

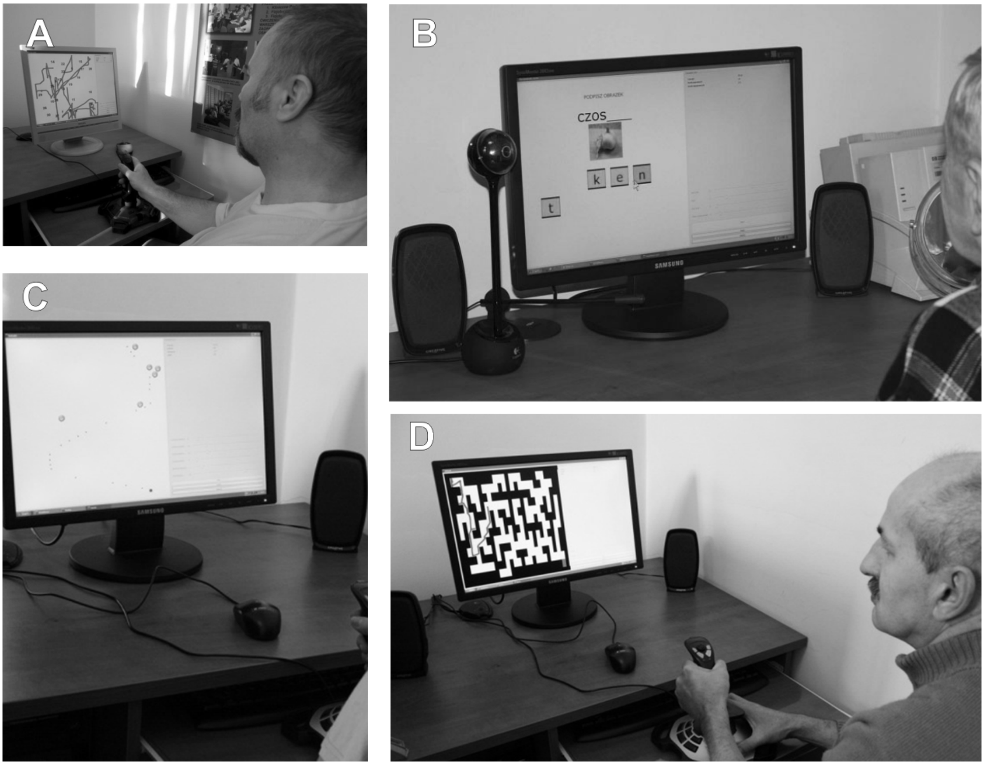

Figure 1. Sample exercises.

5.1. Aphasia

Aphasia is defined as an impairment in the comprehension and use of language, usually triggered by damage to the speech area of the brain. The most common cause of aphasia is stroke. The aim of therapy is to improve verbal communication skills. This type of therapy depends the predominant symptoms. The aim is to restore language comprehension, verbal expression skills or the ability to construct logically and grammatically correct sentences. Doctors may choose exercises individually for each patient, depending on the observed symptoms.

During the project a team of IT programmers and doctors jointly developed a set of exercises enabling patients to undergo rehabilitation without constant help from speech therapists. To facilitate this goal it was necessary to adapt existing speech recognition algorithms. Such algorithms had to be able to analyze the speech of people who have trouble with articulation. The intensity of articulation problems varied from patient to patient, making the problem more complicated. Three levels of speech were defined:

- Recognition of speech events – in this case it is not important what the patient said: information that anything has been said in the specified time is sufficient.
- Recognition of speech from a very limited set of words – a good example is an exercise in which the patient is expected to provide "yes" or "no" answers, or an exercise in which three animals are presented and the patient has to choose one of them (the system should recognize if the patient said "cat", "dog" or "chicken").
- Full speech recognition – any utterance is analyzed.

Although preliminary results appeared encouraging, two specific problems prevented these exercises from being developed further:

- Patients performed these types of exercises unwillingly, preferring to talk to another person rather than to a machine. The need to communicate with another human being was so strong that rehabilitation with speech therapists produced much better results.
- Differences in patients' speech caused by articulation problems were too broad for the algorithms used, resulting in frequent errors.

5.2. Manual dexterity

This group of exercises focused on mental faculties such as matching and planning. The patient not only had to demonstrate manual dexterity by controlling a cursor, but also plan correct execution of the exercise (e.g. solving a maze).

Traditional game controllers are used during manual rehabilitation. They are cheap, widely available and can be applied for remote rehabilitation. Symmetric joysticks are available during rehabilitation at the centre, where patients can perform exercises using either hand.

5.3. Memory and cognition

Exercises from this group are designed to improve visual and verbal memory, processing of information and other mental faculties. Patients can perform exercises using a keyboard, mouse or joystick (e.g. to indicate the correct answer).

5.4. Training courses

A set of exercises selected for a specific patient is referred to as a training course. Training courses may additionally specify the order of exercises, the number of repetitions and values of parameters for each exercise. Any number of training courses can be defined for each patient – the doctors may then choose which course should be performed at the beginning of each rehabilitation session.

One course may contain exercises that target different disabilities, avoiding monotonous repetition and producing better results.

When defining training courses for a new patient, doctors may use existing courses as templates. These templates may be copied and tuned to the new patient's needs. This simplifies and accelerates the process of preparing new courses.

5.5. List of exercises

The available exercises are listed below (note that some exercises have several variants):

- picking squares (variants: standard, random squares, coloured squares),
- picking digit sequences (variants: ordered, random, cf. Figure 1A),
- pairing photographs with descriptions (variants: animals, everyday objects, food),
- filling gaps in the text,
- understanding names (see Figure 1B),
- shooting balloons (variants: standard, with avoidance of marked balloons, coloured balloons, see Figure 1C),
- visual memory (image memorization),
- daily schedule memorization,
- solving a maze (cf. Figure 1D),
- spatial relations (variants: matching images to descriptions, matching descriptions to images),
- naming objects,
- naming spatial relations,
- antonyms of sentences (choosing a sentence with a meaning opposite to a given one, with picture cues),
- antonyms (choosing a word opposite to a given one; variants: verbs, nouns, adjectives, adverbs),
- synonyms of sentences (choosing a word similar to a given one in the context of a sentence),
- abstract memory (responding in an appropriate way to a displayed symbol),
- names in a sentence (matching grammatically correct forms; variants: matching descriptions to pictures, completing sentences with words in an appropriate grammatical form),
- sequences (reconstruction of sequences from memory),
- crossing characters out from a text.

Exercises which employ a virtual reality glove have been created as well to test possible improvements to the system (see section 8) but still further research is needed before they are released. They cover hand gestures, bending and straightening fingers (requires a virtual reality glove), lifting a cylinder (requires a virtual reality glove).

6. Remote rehabilitation

Remote rehabilitation enables patients to perform exercises at home following their main rehabilitation stage [12, 24]. Minimum requirements for remote rehabilitation are listed below:

- computer with Windows 7, Vista or XP,
- caregiver with rudimentary computer skills,
- joystick for manual exercises.

An Internet connection is recommended but not necessary to perform exercises.

Patients chosen to continue rehabilitation at home and their caregivers are appropriately trained during the main rehabilitation stage. The aim of this process is to enable patients to adapt to changes in the rehabilitation regime (shifting from the rehabilitation centre to their own homes).

The initial phase of remote rehabilitation (first several weeks) is strictly supervised by physiotherapist and technical personnel whose task is to ensure smooth transition of rehabilitation from hospital to home, solving potential problems both with exercises and technical issues.

The remote rehabilitation system works on the basis of a client-server architecture, as shown in Figure 2. The most important element of the system is a database server which contains all data representing patients, their training courses and results. It uses a relational database and is hosted at the rehabilitation centre.

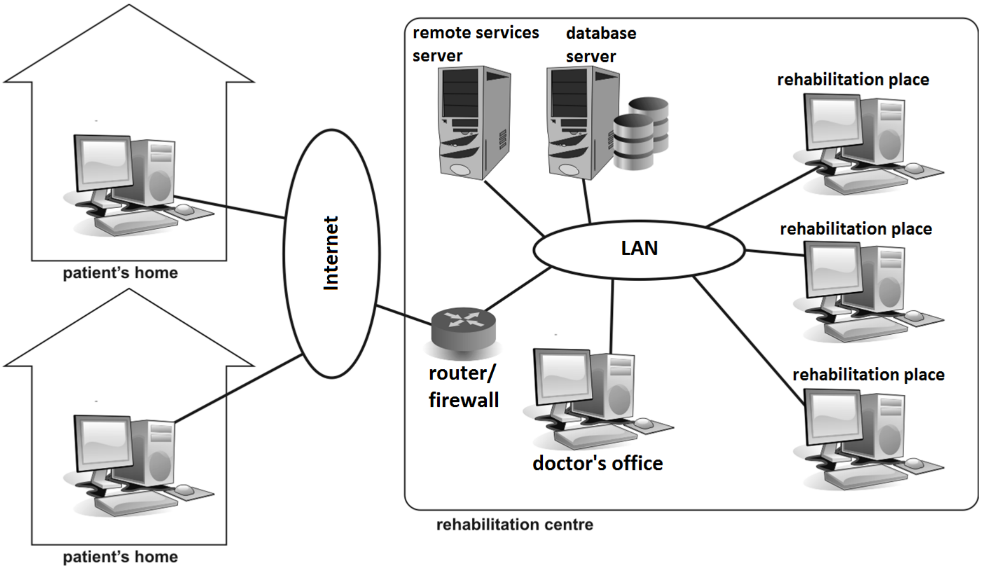

Figure 2. Architecture of the system [23].

To perform exercises the patients may use two types of client applications:

- Application installed on computers at the rehabilitation centre. While allowing all patients to perform exercises, it also supports management of exercises and rehabilitation results, representing the local client mode of the system.
- Application installed at the patient's home. From the patient's point of view, there is no difference between this type of application and the application installed on the computer at the rehabilitation centre so there is no need to familiarize patients with a new user interface. This type of application has limited management features since its main purpose is to operate in a remote client mode.

Patients who use the second type of application cannot connect directly to the remote database server, located at the rehabilitation centre – this server is only visible in a local network (due to security constraints). To provide patients with the ability to upload their results and update exercises, a remote service server was introduced. This server is responsible for authentication and encryption (communication is encrypted to protect patient data from unauthorized access). All communication between remote clients and the database passes through this server (see Figure 3).

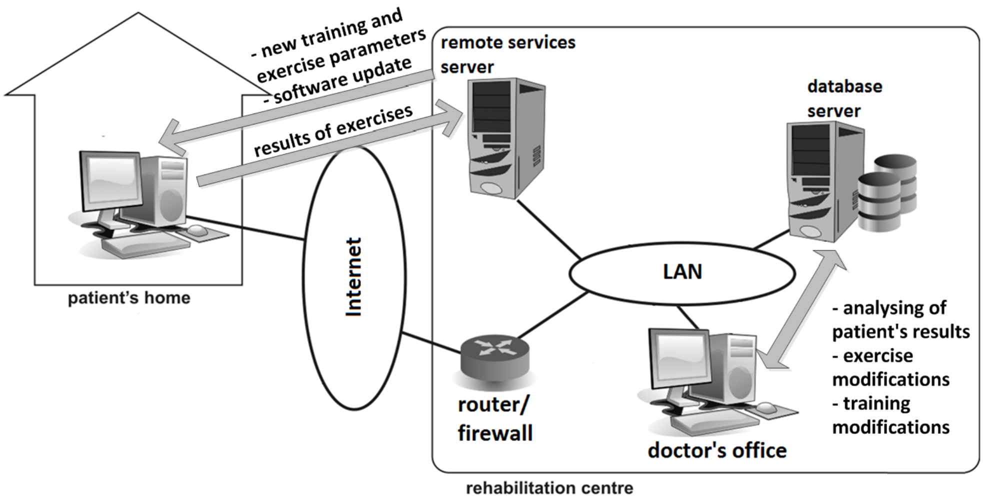

Figure 3. The data flow [25].

Figure 4 shows modules of the client and server applications. The architecture of the server is layered. The endpoint layer provides authentication and encryption. The mediator layer is responsible for serialization (e.g. to XML). The final layer is responsible for message management.

The architecture of the client is much simpler. The latter (remote) type of client application uses a local database, enabling it to operate even when offline. This database stores information about exercises, training courses and results for a specific patient (user of the application). Upon startup the patient's application attempts to connect to the remote application server (see Figure 5). If successful, the application asks the server for the patient's training courses (synchronization of exercises and courses). If synchronization fails (e.g. due to a connection error), the application can still be used to perform exercises (however, it uses data from its local database which may be out of date). In this case, synchronization occurs the next time the application is started, if an Internet connection is available. When the course ends, the patient's application checks which results have already been uploaded. If a server connection can be established, the application uploads all results that haven't yet been sent (including results from the recently completed course). If the patient's application does not receive an acknowledgement, these results are reuploaded following completion of the next course. The local client application does not use a local database or proxy server – it sends results and downloads data directly from the database server (since it is installed on computers at the rehabilitation centre, no encryption or authentication are needed).

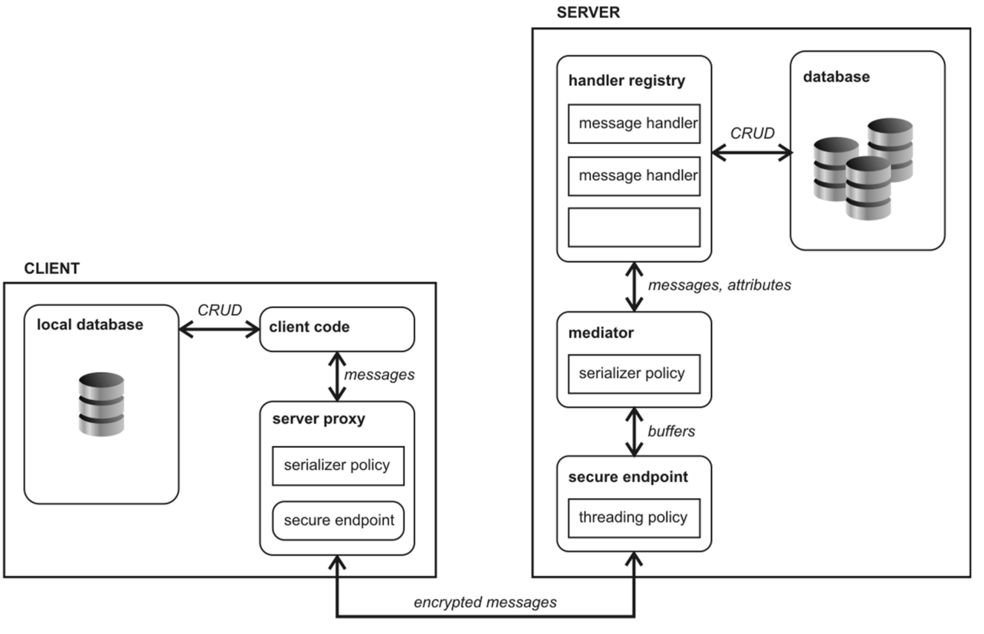

Figure 4. Modules of client and server [13].

The C++ language was used in the development of both client and server applications. In addition, the Qt environment was chosen to provide a graphical user interface for the client application. The server uses the MySQL database engine while clients use SQLite databases (selected due to their low requirements and the ability to run on old or low-end computers).

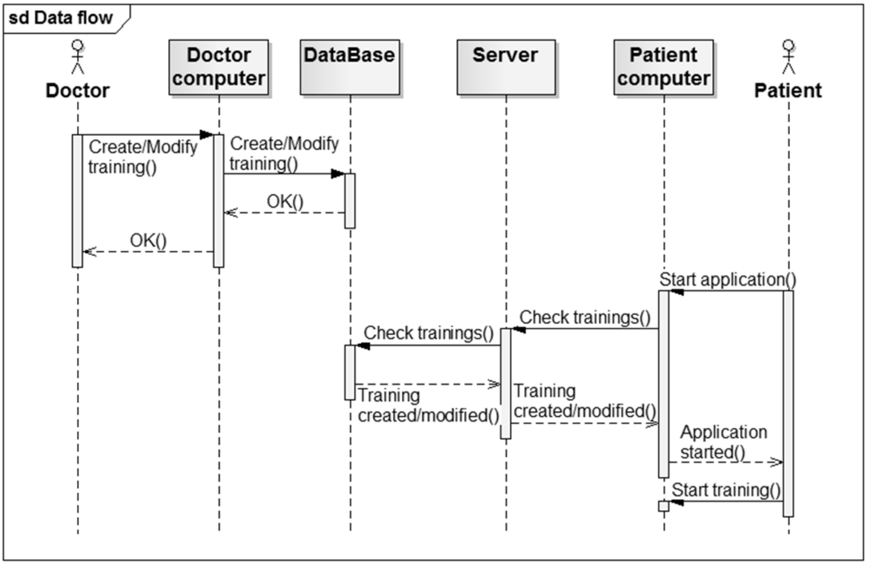

Figure 5. Startup process for the second (remote) type of client application.

7. Results

All tests were performed at the Rehabilitation Clinic of the Jagiellonian University Medical College in Cracow. This section presents results for patients prior to and following a three-month therapy, organized in two series. Table 1 shows the number of patients who participated in rehabilitation.

Table 1

Number of patients who participated in rehabilitation.

Row description	Patients with concentration and memory dysfunctions		Patients with aphasia	
	Series 1	Series 2	Series 1	Series 2
women	6	11	7	11
men	6	19	14	22
total	12	30	21	33

Standard psychological tests were used to grade the effects of rehabilitation:

- For patients with concentration and memory dysfunctions (for both series):
  - Standard medical test MMSE (Mini Mental State Examination) [8] – this test attempts to quantify the patient's capabilities in five fields: orientation, registration, attention and calculation, recall, language. A result of less than 23 points (maximum score is 30) indicates cognitive impairment.

  - Selected parts of Wlodzimierz Łucki's package [16] – visual and auditory memory were taken into account.
  - Aleksander Łuria's learning curve – a test of auditory memory. A list of 10 words is presented to a patient who is given 10 attempts to memorize them. Following each presentation of the list the patient tries to repeat the presented words. 30 minutes later the patient is again queried to check how many words he/she has memorized [26].
- For patients with aphasia (for series 1):
  - Selected parts of Wlodzimierz Łucki's package – language expression and comprehension were taken into account.
- For patients with aphasia (for series 2):
  - Selected parts of Wlodzimierz Łucki's package – various language tasks such as naming common objects, activities or parts of the body, repeating syllables, words and sentences, enumerating days of the week, names of the months, consecutive numbers, comprehension of simple and more complex sentences, reading words and sentences, writing letters, syllables and sentences. Each point scored means that a single word or sentence has been correctly understood by the patient.

Tables 2 [19] and 3 [25] show the results for patients with concentration and memory dysfunctions, while Tables 4 [19] and 5 [25] show the results for patients with aphasia.

Table 2

Results for patients with concentration and memory dysfunctions before and after therapy (series 1).

Row description	Mini Mental State Examination		Memory (W. Łucki set)		Learning curve (max 10)
	general score (max 30)	attention (max 5)	visual memory (max 15)	auditory memory (max 16)	
before	23.6	2.75	8.25	5.0	2.40
after	25.4	3.25	10.6	5.6	3.75
progress	7.6%	18.2%	28.5%	12.0%	56.3%

Differences in the results of visual memory tests were statistically significant ($F[1,54] = 5,80$, $p < 0,01$). The tests were performed prior to and following rehabilitation. Patients who had undergone rehabilitation also memorized a significantly greater number of words in the Learning Curve test ($F[1,54] = 4,8$, $p < 0,03$).

Differences in the results of the tests measuring auditory memory and in results of the MMSE attention test were not statistically significant ($F[1,54] = 0,49$, $p < 0,48$). However, in both tests the average results showed improvement following rehabilitation. Training of auditory memory improved the patients' ability to retrace structured text. The number of correct answers in the attention test also increased following rehabilitation but the differences were not statistically significant ($F[1,54] = 1,11$, $p < 0,29$).

Table 3

Results for patients with concentration and memory dysfunctions before and after therapy (series 2).

Row description	Mini Mental State Examination		Memory (W. Łucki set)		Learning curve (max 10)
	general score (max 30)	attention (max 5)	visual memory (max 15)	auditory memory (max 16)	
before	24.9	3.1	8.3	5.4	3.4
after	26.1	3.5	11.0	6.4	4.6
progress	4.8%	12.9%	32.5%	18.5%	35.3%

Table 4

Results for patients with aphasia before and after therapy (series 1).

Row description	Motor aphasia (Broca)		Mixed aphasia sensorimotor	
	expression	understanding	expression	understanding
before	73.0	59.6	42.8	33.0
after	94.3	67.2	62.6	47.75
progress	29.2%	12.8%	46.3%	44.7%

Table 5

Results for patients with aphasia before and after therapy (series 2).

Row description	expression	understanding	reading	writing
before	45.21	30.78	13.81	7.18
after	61.30	40.08	16.49	9.30
progress	35.6%	30.2%	19.4%	29.5%

The relationship between the results of cognitive function tests, patient age and time elapsed between the injury and the start of training was also analyzed. However, correlation coefficients did not reveal any significant dependencies.

Results for patients with aphasia show that differences in speech expression prior to and following rehabilitation are statistically significant ($F[1,54] = 4,40$; $p < 0,04$). Improvement in speech understanding, writing and reading was lower ($F[1,54] = 1,99$; $p < 0,16$), however, tests which examined reading and writing skills were treated as an additional scope of the therapy.

Additional analysis of correlations did not reveal any relationship between the degree of improvement in speech expression/comprehension and patient age. There were no possibility to create a reference group of patients who received traditional therapy in the same time because the number of patients who participated in the rehabilitation was too small.

8. Conclusions and future work

We are able to formulate some conclusions about patients' and doctors' subjective feelings on the basis of interviews with them. The patients felt that the proposed method helped them. The results of training were easy to understand and available immediately so they were able to observe the progress. It motivated them to work harder.

The doctors willingly cooperated in the testing. Subsequent test sessions with patients allowed finding important elements from the patients' point of view that were very difficult to be foreseen during the design, even when experts had been involved, e.g. a small object in the background of an image might distract patient from the item on which he/she should focus. Stroke patients often pay attention on different elements than healthy people so it is almost impossible to develop an exercise that is suitable for all patients without testing. Doctors cooperation in the testing not only allowed for better adjustment of exercises to patients' requirements but also allowed doctors to gain valuable knowledge about elements that they needed to pay attention on.

The doctors found the proposed method as an interesting alternative for traditional methods. The ability to adjust exercises to the patient's needs (changing parameters' values) has been recognized as a very useful functionality. The doctors from the Rehabilitation Clinic of the Jagiellonian University Medical College in Cracow decided to use the system after the project ending. Although the presented system is fully implemented and allows patients to continue rehabilitation at home, a chance that the method will be widely used in practice in close future is not high in our opinion. We think so because supervising holistic rehabilitation that addresses more than one type of impairment remains a challenge, requiring employment of skilled personnel in many domains (doctors, psychologists, physiotherapists), which may be too expensive for small rehabilitation centres. To deal with this limitation, a novel service model which offers shared access to distributed rehabilitation and a distributed medical knowledge base, is under study. We propose to create a model based on the virtual organization paradigm [11, 14, 15, 28] (see Figure 6). In this model the virtual organization (VO) can be used to provide a backbone for cooperation of rehabilitation centres. This solution would enable patients to rehabilitate at the nearest centre while under supervision of a more distant centre. Owing to the use of virtual organizations, small rehabilitation centres do not need to employ personnel experienced in all areas of rehabilitation, as a single specialist may supervise patients undergoing rehabilitation at different centres. Additionally, this solution facilitates migration of care for some exercises performed by the patient (or migration of patients between centres).

We propose to develop a knowledge sharing system within a single virtual organization (cf. Figure 7). This system would aggregate large amounts of relevant data from many patients, supporting an automatic recommendation module which could help doctors select appropriate exercises for each patient and automatically update their parameters during rehabilitation (to dynamically adapt to the growing potential of each patient). This system may use correlations between patient progress and the exercises performed, their parameters, frequency, order of execution etc. Although knowledge sharing is a key concept in this novel service model, confidentiality and privacy of patient data have to be ensured. We therefore propose to store all data locally (at the rehabilitation centres) and only share knowledge inferred from anonymized patient records (see Figure 7).

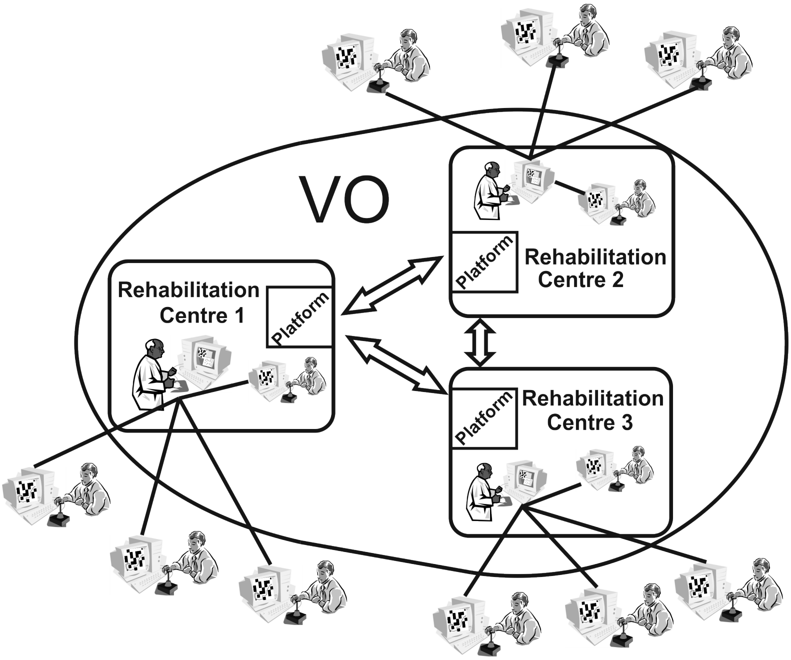

Figure 6. Virtual Organization approach to the remote rehabilitation process.

Other possible paths of improvement of the presented system include:

- Further extension of the set of rehabilitation exercises – adding new exercises is supported by the object-oriented system architecture. Additional exercises can be prepared to adjust the rehabilitation program to patients' individual needs and to make rehabilitation more interesting.
- New rehabilitation equipment, such as parapodium, bicycles and haptic devices, may be used to control exercises. This would make exercises more attractive while at the same time producing useful data regarding the execution of exercises.
- Introducing more autonomous features to the system in order to support selection of proper rehabilitation strategy, individually adopted to patient's needs, using semantic and expert approach, adopted from other fields of computational system engineering (e.g. [7]).

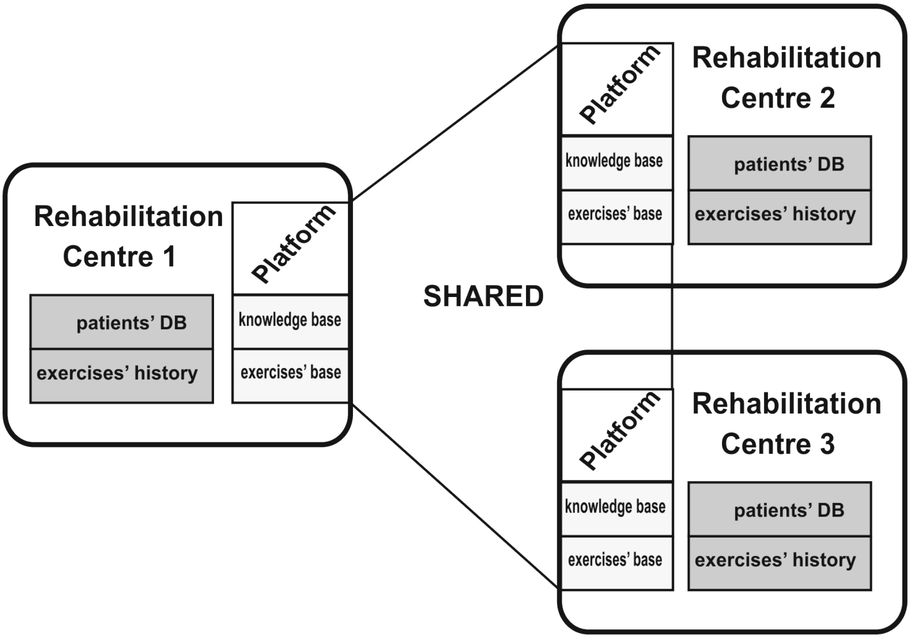

Figure 7. Knowledge sharing system.

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