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Development of a Systems Architecture for Robot-Aided Telerehabilitation

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1. Introduction

Given the rapid increase in the aging of the population and the further increase that is expected in coming years, an important problem that has to be faced is the corresponding increase in chronic illness, disabilities, and loss of functional independence endemic to the elderly (WHO 2008). For this reason novel methods of rehabilitation and care management are urgently needed. Among the various health problems affecting the elderly, there is no doubt that stroke shows no sign of relinquishing its status as the leading cause of adult disability. After the acute phase all patients require continuous medical care and labour intensive rehabilitation. Arm therapy is used in the neurorehabilitation of patients with upper limb paresis due to lesions of the central nervous system (Riener et al., 2005). Besides traditional physical therapy, task oriented repetitive movements can help patients recover motor function, improve motor coordination, learn new motor strategies and avoid secondary complications, as many studies using robot-aided therapy attest (Krebs et al.,1998; Volpe et al., 2000; Lum et al., 2002, Colombo et al., 2005; 2008). Over the past decade, computer and information technologies have become increasingly available and cost-effective as a means of providing educational and health care services. Telerehabilitation is the delivery of rehabilitation services through a telecommunication network and the internet (Russel, 2009; Telerehabilitation – Wikipedia). A recent study that performed a systematic review of clinical outcomes, clinical process, healthcare utilisation and costs associated with telerehabilitation (Kairy et al., 2009) found, apart from experiments in various disciplines pertaining more to the field of telemedicine, only 28 studies that were strictly classifiable as telerehabilitation applications. Although these studies were heterogeneous in terms of study design, type of patients, settings and outcomes measured, a consistent trend was found in terms of their support for the effectiveness of telerehabilitation. The majority of them implemented programs of physical therapy remotely supervised by means of standard videoconferencing low-bandwidth systems.

The scenario of applications demonstrating the potential for remote diagnosis and treatment through robot-aided telerehabilitation is quite recent. In particular, the feasibility of remote training of arm movement using force feedback devices in stroke patients was first demonstrated by Reinkensmeyer et al. (2002) using the so-called Java Therapy system and successively updated with the T-WREX device (Sanchez et al., 2006). Another laboratory application successfully tested the use of a virtual reality-based telerehabilitation system in five post-stroke patients (Piron et al., 2004). The Rutgers master II (RMII), developed by Popescu et al. (2000) was used to increase hand strength in stroke patients using teletherapy. Lum et al. (2006) developed a device called AutoCite that automates the intensive training component of constraint-induced movement therapy, and evaluated its effectiveness in a telerehabilitation setting under remote supervision by a therapist. Recently, Carignan et al. (2006) evaluated the potential application of the InMotion2 Robot (the commercial version of the MIT-Manus) for cooperative telerehabilitation in which the therapist and patient interact directly with each other over the internet both visually and kinesthetically. All these studies demonstrated the feasibility of the telerehabilitation approach and, in addition, Lum's study demonstrated that the gains in motor ability obtained with remote supervision were comparable with those obtained with direct supervision. None of these experiences tried to base their architecture on more than one type of rehabilitation device, i.e. none aimed to apply a modular combination of devices that can cover a larger population of patients.

Telerehabilitation may well be able to optimize the therapeutic intervention, despite the fact that the patient does not directly interact with the therapist . This is so not only in the home care setting, but also in the clinical setting where it makes it possible for a therapist to monitor several patients at once, at their training stations located in different laboratories. The connected devices can be diversely configured in order to target the rehabilitation of different joints and motor tasks.

The main advantages of telerehabilitation are that it allows:

- improved continuity of care, through a choice of technological services designed to assist patients as their needs change;
- increased exercise time and intensity for a quicker recovery of the patient, obtained without a corresponding increase in resources allocation and possibly through a more cost-effective application of intensive treatments;
- continuous, real time monitoring of the effects of the treatment session, using video and physiological signal transmission;
- on-line tuning of exercise parameters;
- concurrent monitoring of multiple treatment stations.

This chapter presents a preliminary experience carried out in our Rehabilitation Institute to verify the feasibility of implementation of a telerehabilitation approach based on the application of robotic devices developed in our research laboratories.

2. System Design

2.1 Rehabilitation Devices.

Although virtually any robotic device developed for upper or lower limb rehabilitation can be employed for remote supervised training, in practice the larger, more complex, more expensive devices are reserved mainly for the clinical setting, while the home care setting calls for smaller, cheaper and easy to use devices.

The systems architecture implemented in our experiments consisted of three devices developed for upper limb rehabilitation that can be employed in either setting:

1) a one degree of freedom (DoF) wrist manipulator specifically designed for the rehabilitation of wrist flexion and extension movement.
2) a two DoF shoulder elbow manipulator called MEMOS which allows robot-aided therapy by administering a sequence of reaching movements in the horizontal plane [6].
3) a graphic tablet-based device developed to improve the quality of movement (accuracy, efficiency and smoothness) in patients with mild impairment.

The systems are based on the execution of repeated voluntary movements and on the consequent motor learning phenomenon. The patient is facing a video screen that provides visual feedback in the form of three coloured circles as follows: 1) a yellow circle indicates the task's starting position; 2) a red circle indicates the task's target position; 3) a green circle indicates the current position of the handle. The first two devices are admittance control based; this means that the patient exerts a force on the handle of the device which in turn produces a displacement. Three possible control strategies were implemented: a) completely servo-assisted movements; b) shared control of the movements (i.e. the system will help the subjects to carry out the part of the task they are not able to do autonomously); c) completely voluntary movements. Seamless transition among the control strategies was applied, in the sense that if a time period of more than 3 s. elapsed in which the patient was unable to move the handle, the device would 'take over' and complete the motor task. Details of the systems can be found in Colombo et al. (2005; 2008). The tablet-based device shares the same user interface and features as the two DoF devices but, of course, does not provide assistance when the patient is not able to complete the assigned motor task. This system is applied in a different laboratory where patients practise activities of daily living (ADL) to improve the quality of their movements. This type of practice might be very useful in post-stroke, TBI patients and subjects with ataxia.

2.2 Systems Architecture

The systems architecture implemented is represented in figure 1. It consists of a number of rehabilitation stations (a maximum number of 16 was selected) and a supervision station, located in different laboratories. They are all interconnected by means of a standard Ethernet II network. The supervision station includes also connection to the internet in order to connect remote rehabilitation stations in the home setting. In this preliminary presentation only the in-clinic subnet will be discussed.

Rehabilitation Station: it consists of a rehabilitation device (robot or tablet) and web cam directly connected to the network (IP camera). This configuration enables both video/audio and exercise monitoring. It exchanges information with the supervision station in order to implement the following functions:

a) activate the exercise by means of a program interface easily manageable by the patient; b) allow remote setting of the exercise parameters (protocol, duration, maximum speed, duration of rest, etc.); c) manage exercise execution during each session; d) collect and store data from the rehabilitation device; e) compute evaluation parameters in order to quantitatively measure patient performance during exercise execution; f) compute and display in real time, during the task execution, scores providing visual feedback to the patient of their performance; g) allow video/audio communication with the supervision station.

Supervision Station: it represents the central node of the network, where the therapist manages all the activities of each rehabilitation station. Consisting of a remote workstation, it: a) selects the patients to be supervised; b) sets up the rehabilitation protocol and, if required, modifies the exercise parameters; c) monitors in real time the patient's performance by means of specific charts; d) transfers and archives the data and parameters acquired by the rehabilitation station; e) stores the collected data in a central data base; f) post-processes the collected data; g) reviews performance charts and allows comparison of charts; h) prints performance reports; k) allows audio/video communication with the rehabilitation station, in order to implement one-to-one and one-to-many therapist to patient interaction.

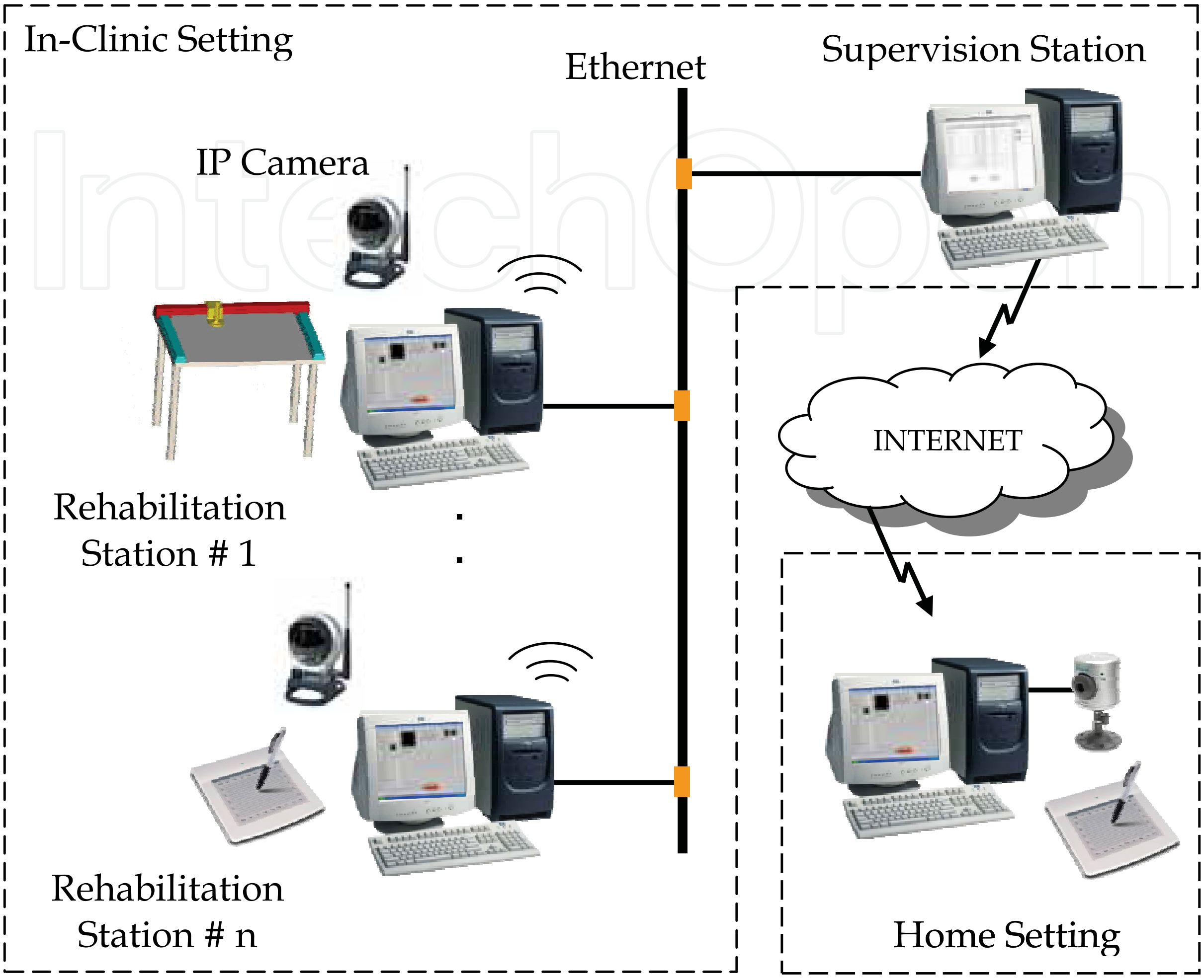

Fig. 1. Systems architecture implemented for telerehabilitation.

Audio/Video monitoring: diverse audio/video features are possible depending on the type of video camera selected. Two-way video conference-like communication using a webcam with pan, tilt and zoom functions can be selected to carry out full audio and video one-to-one interaction (figure 2a). This feature is crucial when the therapist needs to monitor fine movements, like finger movements, with an appropriate resolution. In this pilot study we tested a network-camera (Linksys WVC200) which allowed full videoconferencing with the patient during the motor task execution. With this implementation we could also monitor several patients at the same time so allowing one-to-many telemonitoring (figure 2b).

2.3 Software Implementation

Both the Rehabilitation and Supervision stations were developed using LabWindows CV/I software development environment (National Instruments, Austin-TX,USA). The features of the former have been described elsewhere (Colombo et al., 2005). The application program of the Supervision Station has the following main features:

a) it monitors the current status of the configured devices (device on-line/off-line, patient active/non-active);

b) it remote-configures the exercise. This is typically done by the supervising therapist when a new motor task needs to be configured or the difficulty level of the exercise adjusted. This function (implemented through the UltraVNC program, http://www.uvnc.com) allows the therapist to use the mouse and keyboard of the supervision station to control the rehabilitation station remotely. It means that the therapist can work on a remote computer, and from this location control the rehabilitation station as if seated in front of it.

c) it displays patient performance charts. These display the time course of some parameters measured by the robot. For example for the shoulder and elbow manipulator the charts display the performance score and the parameters measuring the efficacy, accuracy, efficiency and mean speed of movement (see next paragraph for more details). On demand, raw data can be transferred and stored in the supervision station data base.

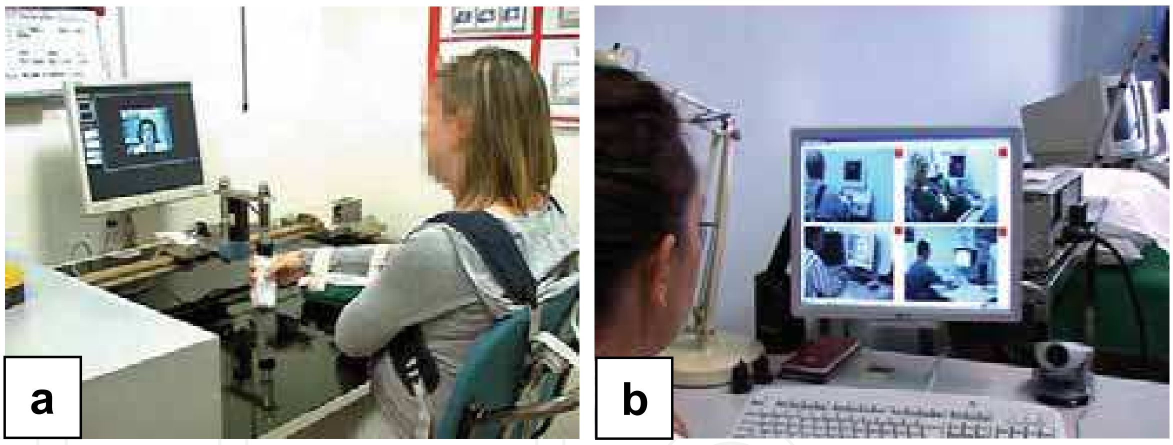

Fig. 2. a) One-to-one and b) One-to-many therapist to patient interaction examples.

3. Telerehabilitation Example

This systems architecture was tested during the rehabilitation of four patients after chronic stroke. The testing was preceded by a learning phase in which patients were trained in order to be autonomous in the phase of connection to the device and start of the exercise. If the patient could not attain autonomy for this task the caregiver was instructed to attach the patient to the device.

Thanks to the remote control program the therapist could take complete control of the remote device and select a new motor task when a change in difficulty level was required. The values of the exercise parameters were logged into a file of the rehabilitation station. In this way the settings of the previous session could be used as default for the following exercise session.

Figure 3 shows the patients' performance charts obtained during the telerehabilitation preliminary study. Top panels present the charts of two patients during treatment with, respectively, the tablet-based device (left panel) and the shoulder-elbow manipulator (right panel). Bottom panels present respectively the charts of a patient during the course of treatment with the wrist manipulator device (left panel) and those of a patient taken from our patient files. Each chart reports the mean value of some performance parameters measured during the training. Blue points and lines represent the values obtained for each parameter during previous training sessions. The point in red represents the current value during the ongoing session. Current values were updated on the supervision station every 10 s by means of a polling operation. The rehabilitation station acquired and collected the raw data including the position of the robot handle, the patient's exerted force, and the robot status. On demand, raw data could be transferred and stored in the supervision station data base.

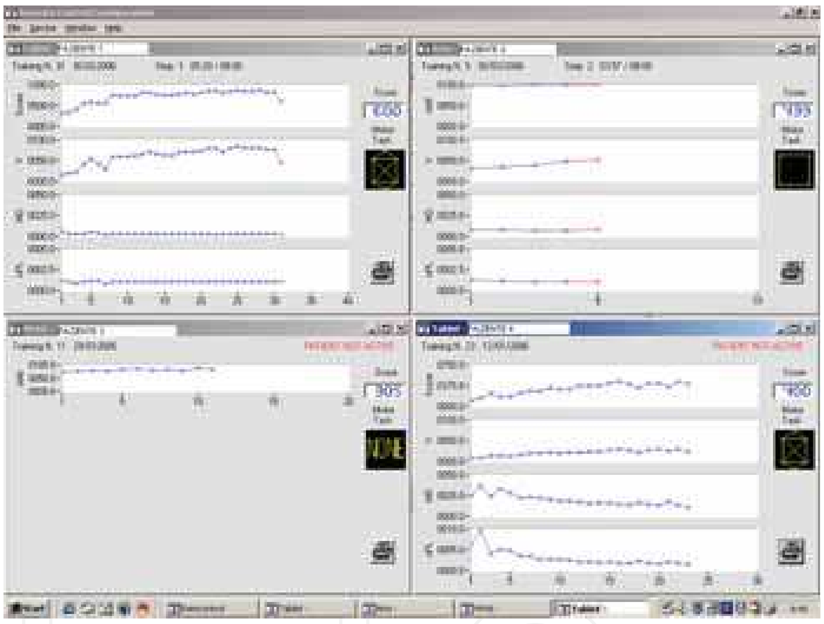

Fig. 3. Patients' performance charts obtained during the telerehabilitation test.

Figure 4 presents a typical example of the time course of the device measured parameters during the treatment of a patient after chronic stroke. In particular, the shoulder-elbow manipulator included the following parameters:

Movement efficacy. The movement efficacy was measured by computing what we called the active movement index (AMI) that quantified the patient's ability to execute the assigned motor task without robot assistance. A score termed ‘robot score’ was displayed on the video screen facing the patient during task execution. It increased only during the patient's voluntary activity, reflecting the proportion of theoretical path (i.e. the straight line connecting the starting point and the target) travelled by the handle thanks to the patient's force. The robot score was expressed as a tenth of the total distance between the starting point and the target. The AMI was calculated as the ratio between the robot score obtained by the patient and the theoretical score, i.e. the score obtained if the patient completed all tasks of the training session by means of his voluntary activity. In order to obtain a normalized index it was expressed in percentage units.

Movement speed. The training device allowed to record the current position of the handle. In this way the mean value of the velocity (VM) of the handle during the task execution could be computed.

Movement accuracy. The accuracy of the movement was assessed by measuring the mean absolute value of the distance (MD) of each point of the path from the theoretical path. When this parameter approximates zero movement accuracy will be very high. It is actually a measurement of the error of accuracy; hence a decrease in this index during training indicates an improvement of accuracy in the motor task execution.

Movement efficiency. The movement efficiency was obtained by computing the path length (nPL) of the trajectory travelled by the patient in order to reach the target. This parameter is virtually the line integral of the trajectory over the time taken to reach the target. In practice it was obtained by summing the distances between two consecutive points of the patient's path; it was normalized to the straight line distance between the starting point of the task and the target. Also this parameter is a measure of the error of movement efficiency; hence decreasing values during training should reflect an improvement of efficiency of the motor task execution.

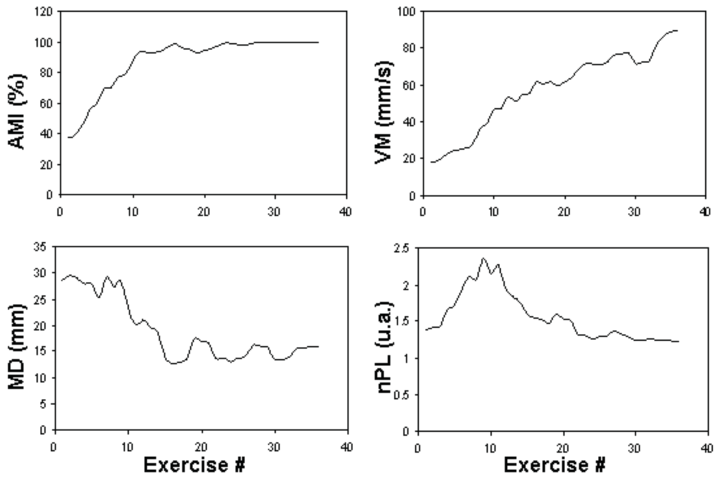

Fig. 4. Example of the time course of the device measured parameters during the treatment of a patient after chronic stroke.

In this example one can note that the AMI increased up to half-way through treatment, at which point the patient was able to complete the motor task. The mean speed VM was constantly increasing, indicating continuous improvement of the patient's performance throughout the treatment. The mean distance (MD) and the normalized path length (nPL) errors decreased, thus showing an improvement in both accuracy and efficiency of the movement.

4. Human factors in robot-aided telerehabilitation

Despite the fact that telerehabilitation is strongly based on technology, it is essential that all telerehabilitation services are designed and implemented with the users in mind. We must consider as users both sides of the communication channel, i.e. the patient and the therapist. It is thus extremely important that human factors are considered in the planning and implementation of the telerehabilitation programmes and in the design of new devices (Brennan DM et al., 2008). In particular, the technology employed should be easy to use both for the therapist and patient. A simple user interface, an easy way to interact with the system and an environment that does not distract the patient are fundamental prerequisites. The systems should be flexible enough to support the diverse requirements due to the different age, education, technology experience and level of impairment of patients, so as to maximize patients' acceptance and motivation and minimize the effects of their disabilities. Another key factor is training. Patients should receive clear, detailed information about the technology in view of the fact that the home care setting will be a reduced supervision environment. The possibility to implement both videoconference communication and remote management and monitoring of the devices should be considered an add-on value of our architecture able to soften the impact of technology.

IMI subscale	*Score (Mean ± S.D.)*
Interest/Enjoyment	6.00 ± 1.49
Perceived Competence	4.59 ± 1.89
Effort/Importance	6.70 ± 0.72
Value/Usefulness	6.15 ± 1.38
Pressure/Tension	2.26 ± 2.07
Pain	2.39 ± 2.28

Table 1. Subscale findings of the Intrinsic Motivation Inventory questionnaire evaluated in patients treated with the elbow-shoulder rehabilitation device (subscale range= 1–7).

Motivation is an important factor in rehabilitation and frequently used as a determinant of rehabilitation outcome. Several factors can influence patient motivation and so improve exercise adherence. In a previous study (Colombo et al., 2007) our research group assessed patient motivation in a group of post-stroke patients who underwent treatment by means of robot-aided neurorehabilitation in an in-hospital setting. Patients' motivation was assessed by means of the Intrinsic Motivation Inventory (IMI) questionnaire (17-item version). The results are reported in Table 1.

The interest/enjoyment subscale, that is considered the self-report measure of intrinsic motivation, obtained a high score. This means that our patients found the robot therapy very interesting. The perceived competence subscale resulted in a mid score. This result is not surprising given the different level of disability of our patients. In fact, less compromised patients should obtain better results than more compromised patients. Also the effort/importance and value/usefulness subscales obtained a high score, demonstrating that patients were really motivated in doing this type of treatment and were satisfied with the results obtained. In particular, they perceived that the treatment had a positive result in terms of improving their disability. The pressure/tension and pain subscales obtained a low score. This means that the majority of patients did not experience tension or pain during the training with the robot device.

Recently Piron and colleagues (2008) measured the satisfaction with telerehabilitation care in post-stroke patients. They compared the degree of satisfaction of two groups of patients undergoing a virtual reality (VR) therapy programme: at home versus in a hospital setting. Patient satisfaction was measured through a 12-item questionnaire administered at the end of treatment. The questionnaire included items assessing the usability of the VR system, the relationship with the therapist and overall satisfaction with the treatment. Patients treated at home with the telerehabilitation approach showed median values equal to or higher than those obtained in the in-hospital group. In addition the first group improved significantly their motor performance, while the latter group showed no significant change.

Question	*Score (Mean ± S.D.)*
1. I need to monitor patient performance during remote supervision.	5.9 ± 1.7
2. I need to modify the exercise parameters (duration, difficulty level, task shape, etc.) during remote supervision.	6.6 ± 0.8
3. I would like to be able to remotely feel the patient's exerted force during the exercise execution.	5.2 ± 2.0
4. I think that robot-aided telerehabilitation can be useful in the home setting.	5.1 ± 2.0
5. I think that robot-aided telerehabilitation can be useful in the in-hospital setting.	4.6 ± 2.3
6. I think that robot-aided telerehabilitation can reduce rehabilitation costs.	4.4 ± 2.7

Table 2. Mean score and standard deviation obtained in six questions assessing therapists' opinions about the telerehabilitation architecture. (Score range= 1 -7; 1= not at all true; 7= very true).

To assess therapists' opinions about the architecture presented here and general issues regarding telerehabilitation, we surveyed a group of 18 therapists. They underwent a 1 h briefing session in which they received detailed information about robot aided rehabilitation and telerehabilitation. They were then divided into three groups and underwent a 1 h practice session in which they could conduct a complete telerehabilitation training session using the robots. At the end of the practice session the therapists were asked to fill in an ad-hoc questionnaire. Table 2 reports the results (mean score ± standard deviation) obtained for six specific questions.

The therapists thought it very important to monitor specific exercise parameters (such as accuracy, efficiency, speed, etc.). This means that they consider it important not only to communicate with the patient but also to measure the patient's performance. They expressed the need to be able to remotely modify the exercise (e.g. change the difficulty level of the task, the exercise duration, etc.). They also stated that they would like to feel the patient's exerted force during the exercise performance. This is a feature unsupported by our system at present but we hope to introduce it in future extensions.

Questions 4 to 6 regard general opinions about the telerehabilitation approach. The scores were lower than those obtained for questions 1 to 3, but in any case mid-scale values were obtained. This is due to the fact that there were two main attitudes in favour and against the telerehabilitation approach and consequently high and low scores. It is expected that a longer practice period during real treatment sessions could positively change this result.

5. Discussion and Conclusion

The study presented in this chapter shows the feasibility of implementing a telerehabilitation approach based on the application of robotic devices to increase training intensity in post-stroke patients. The robot-assisted teletherapy was well accepted and tolerated by all patients. The assessment by means of ad-hoc questionnaires of patient and therapist satisfaction with the telerehabilitation approach confirmed a high degree of satisfaction with this type of approach. In addition, the new technological context facilitated therapy planning for the medical professionals and therapists, including the possibility to continue the rehabilitation program in the home setting. Of course, extended application in a consistent group of patients is required to evaluate if the improvement of patients' motor ability obtained through telerehabilitation is similar to that obtained in controlled laboratory conditions. In particular, evidence is needed to show that learning in a telerehabilitation environment can be generalized to a community setting.

Circuit class therapy is a mode of delivering rehabilitation services with a reduced therapist-to-patient ratio. The advantage of this approach is that it offers increased intensity of treatment while at the same time reducing health care costs. However, only patients who can safely perform the required motor tasks may be eligible for this type of therapy. The architecture we implemented can be considered as a sort of technological circuit class therapy to be used with more compromised patients.

A key goal of future research will be to quantitatively evaluate patients' adherence to the prescribed regimen. The remote supervision and the possibility of administering appealing motor tasks specifically adapted to the patient's ability/disability should contribute to enhance their motivation, so improving adherence and involvement.

Some applications have explored the feasibility of using "interactive telerehabilitation" and "cooperative telerehabilitation" (Carignan & Krebs, 2006) i.e. the situation in which both therapist and patient interact directly with each other through the Internet, without any direct force feedback interaction in the former case and both visually and kinesthetically in the latter (patient and therapist have the feeling of being in direct contact with each other through the device). This type of approach involves a one-to-one interaction; thus it would be economically justifiable mainly in situations of long distance between the patient's home and the rehabilitation centre. In addition, it requires the solution of problems of time delay in the control loop due to the network; this delay is not negligible in the case of Internet communication and is highly variable.

The application of one-to-many remote-supervised therapy implies a reduction in the therapist to patient interaction. Such contact could take place at the beginning and end of each session or less frequently. This would allow the patient to concentrate on performing the assigned motor task without being distracted by the technology. Real time video/audio communication might be useful mainly at the beginning of training to provide suggestions for an optimal task execution, and subsequently just for reporting feedback about the obtained performance and sustaining patient motivation. Such approach would have more chances of a successful application because it would combine an increase in the intensity of treatment with a contemporary reduction of health care costs.

Finally, future studies should address the development of new devices such as wearable robotics and wireless sensors in order to give patients the chance to be trained through a telerehabilitation approach directly in activities of daily living.

In addition, further research is needed to set minimum technical specifications and standards, provide safe and fault-tolerant technology, validate clinical protocols, investigate the effectiveness of interventions and establish the cost-effectiveness of robot-aided telerehabilitation. Thus, with a rapid increase in the speed and quality of the telecommunication services, the future should hold bright prospects for the spread of telerehabilitation.

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Population ageing has major consequences and implications in all areas of our daily life as well as other important aspects, such as economic growth, savings, investment and consumption, labour markets, pensions, property and care from one generation to another. Additionally, health and related care, family composition and life-style, housing and migration are also affected. Given the rapid increase in the aging of the population and the further increase that is expected in the coming years, an important problem that has to be faced is the corresponding increase in chronic illness, disabilities, and loss of functional independence endemic to the elderly (WHO 2008). For this reason, novel methods of rehabilitation and care management are urgently needed. This book covers many rehabilitation support systems and robots developed for upper limbs, lower limbs as well as visually impaired condition. Other than upper limbs, the lower limb research works are also discussed like motorized foot rest for electric powered wheelchair and standing assistance device.

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