Computer-Assisted Rehabilitation: Towards Effective Evaluation

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Abstract: Recent decades brought technological advances able to improve the life quality of people with disabilities. However, benefits in the rehabilitation of motor disabled people are still scarce. Therapeutic processes are lengthy and demanding to therapists and patients. Our goal is to assist therapists in rehabilitation procedures providing a tool for accurate monitoring and evolution analysis enriched with their own knowledge. We analyzed therapy sessions with tetraplegics to better understand the rehabilitation process and highlight the major requirements for a technology-enhanced tool. Results suggest that virtual movement analysis and comparison increases the awareness of a patient's condition and progress during therapy.

Keywords: Physical Rehabilitation; Tetraplegic; Therapists; Computer-Assisted Rehabilitation; 3D Visualization.

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1 Introduction

Physical therapy is a relevant therapeutic process to patients recovering from a severe injury. Its main goal is to improve the patient's life quality, through training movements and reactions, thus ensuring a greater independence and control of their body. However, rehabilitation is always a long, arduous and tedious process, as patients are forced to constantly repeat the same exercises, and the progress is usually very slow, taking months or even years until changes are visible or felt.

A physiotherapist has the role to observe, interpret and act to optimize the patient's response abilities. These therapeutic processes are, once again, lengthy and require great dedication and motivation from both therapist and patient. Also, they consist of carrying out repetitive movement patterns across sessions, giving relevance to a suitable observation, analysis and accompaniment process.

This research aims to develop the tools within the therapist's reach and hence improve the overall rehabilitation process. To this end, we studied the daily routines and analysis procedures at a rehabilitation centre (Figure 1), and contribute with a set of limitations and requirements for a technological-enhanced rehabilitation solution for therapists. Our aim is to provide to physical therapists a computer platform, with efficient and accurate mechanisms, for monitoring their patients. These mechanisms include: saving all the movements that the patient performed for further evaluation and visualization, which is likely to improve the exchange of data between therapists; keep the information for later analysis; have a precise and objective measure of the patients and their evolution; and be able to compare movements performed in different sessions.

In this paper, we present the major outcomes from our studies performed with the main stakeholders in a rehabilitation centre. Further, building on the requirements retrieved from the aforementioned analysis, we present a virtual rehabilitation platform and the results from a preliminary evaluation with the target population (the therapists). Results suggest that a platform that is able to accurately record three-dimensional representations of the sessions is a valuable contribution to the therapists and improves their awareness about the patients' status and evolution.

2 A Glimpse on Current Procedures

Every patient is a different challenge for a rehabilitation therapist as they have to identify the person's abilities and work on how to improve them. From person to person, the abilities may vary significantly, and so does their evolution. This is a process where the therapist plays an irreplaceable role but we believe that can be supported by external tools. To do so, the first step was to take a *snapshot* of the current rehabilitation procedures. With this, we intended to understand the needs and limitations the therapists face in their day-to-day sessions.

Figure 1 Traditional Rehabilitation

2.1 Procedure

To better understand the rehabilitation process we carried out a ten (10) day study in a rehabilitation centre with the main stakeholders, i.e. therapists and patients (Figure 1). While we believe our findings to be valuable for the general population, we focused our studies in motor impaired patients as the duration of the therapy may extend for several months and, in most cases, years. This time span and the slow evolution rate demand a good analysis, storage and follow-up process. These challenges are likely to expose the insufficiencies of current procedures.

The analysis was performed with 3 physiotherapists and 7 patients. It consisted on interviews and questionnaires to therapists and patients, and a thorough observation of therapy sessions and exercises. Along two weeks (10 days), we worked closely with the stakeholders, recording every session for later analysis but also by prompting the therapists during the sessions. In the first session, we performed questionnaires to the therapists and the patients, to characterize their daily routines, exercise sets and evolution patterns. We performed interviews after each session, with each therapist, to understand the goals, limitations and difficulties of each exercise set. In these interviews, we were able to identify, together with the therapists, what they wanted to observe and what they actually could observe and register.

Summing up all observations and interviews, we were able to create a list of requirements for patient evaluation and rehabilitation, and a list of the limitations they face with the current *modus operandi*. These data was put up to discussion in a meeting with the three therapists. The outcome was a set of conclusions about the requirements and limitations of current procedures.

2.2 Results

Every patient attending the rehabilitation centre had an individual treatment plan. The number of sessions per week and the duration of each session were also widely variable. The patients in this rehabilitation centre were all individuals with spinal cord injuries, with severe motor impairments. The lesion severity and degree were also variable. This had an effect on the diversity of exercises observed during the evaluation period. However, for the same patient, the exercises were similar in all sessions.

The therapists had a laptop where they wrote notes after the sessions. These notes were stored in text files with no particular format. Files were organized according to date. In some exercises, the saved outcome was limited to a qualitative analysis while in others the therapists tried to evaluate and extract movement metrics (movement amplitude, angles). This information was estimated by the therapists without the aid of any particular tool.

From the observation period, and discussion with the therapists, we highlight the following conclusions:

- Most exercises are performed physically close to the therapist. During its execution, the therapist is unable to take notes or even have a full view of the performed motions or strengths (Figure 1);

- Some exercises are performed locally (e.g., moving an arm) but, to be performed correctly, depend on a set of restrictions (e.g., maintaining the trunk steady). Performing the exercises repeatedly in the wrong way may have a hazardous effect on the patient's rehabilitation. It is hard for the therapist to have a complete view when engaged with the exercise;

- Even the movements observed by the therapist are registered with an approximate value. This value is highly subjective and may vary from a therapist to another. Further, considering the longevity of the process it is impossible to guarantee coherence across evaluations thus damaging the record of the user's evolution;

- The patients have no visual feedback on their movement or its deviation from accurate movement. Therapists have to constantly reproduce their movement and then exemplify how to do it correctly. Even in the presence of a mirror, one that is likely to be available in rehabilitation facilities, the patients are only able to observe a fixed point of view.

From the analysis, we consider that a computer platform supported with an accurate tracking system is a valuable addition to the current rehabilitation procedures. In the proposed system, it is important to highlight both the patients and the physiotherapists as the target populations. For therapists, this system will bring benefits such as information sharing, movement pattern and cross-movement analysis; for patients as it may increase the motivation to achieve the proper movement, as they can receive feedback on their status. In this paper, we focus our contribution on the therapists end.

3 Related Work

Rehabilitation is a process which uses available facilities to correct any undesired motion behaviour in order to reach an expectation (e.g. ideal posture) Sveistrup (2004). Motor recovery is achieved through task-oriented training and repetition intensity Malouin et al. (2003). The potential of technology for rehabilitation was readily apparent, and a great deal of work has emerged (Asato et al. (1993); Kizony et al. (2006); Rand et al. (2004b); Sisto (2008)), involving therapy and playfulness, and contributing to interesting technological and rehabilitation advances.

For instance, Rand et al. (2004a) developed the Virtual Mall, a system where stroke patients could carry out daily activities, such as shopping, allowing them to gain more independence. Jack et al. (2001) proposed a system for rehabilitating hand function, using a CyberGlove and Rutgers Master II-ND force feedback glove. An evaluation with three patients during two weeks showed improvements on most hand parameters.

Holden (2002) developed a training system based on the principle of learning by imitation. The authors used pre-recorded movements of a virtual avatar in order to motivate patients to perform upper limb repetitive training. Evidence shows that the Vivid GX video capture technology can be used for improvements in upper extremity function Kizony et al. (2003). Over the years, several rehabilitation applications have been proposed using this technology (i.e. video capture) Sveistrup (2003); Bisson et al. (1993); Cunningham (1999): a juggling task where the participants are required to reach laterally to juggle virtual balls; a conveyer belt task where participants are required to turn sideways, pick up a virtual box, and deposit the box on a second conveyer belt; and a snowboard task where the user is required to lean sideways to avoid objects while boarding down a hill. One of the main advantages of these applications is its flexibility, allowing the task difficulty to be easily modified (e.g. number of objects, speed, and size).

Although providing engaging exercises to patients is crucial to guarantee the success of technological solutions, most applications ignore the therapist's role on the rehabilitation process. According to our preliminary results, accurate assessment, evaluation and comparison of the patients' motion patterns over time can improve their motor recovery, since therapists can make more informed decisions. Similarly to what happens on medical applications, where motion, posture and gait analysis are used for treatment planning (Davis et al. (1991); Kejonen et al. (2003); Esquenazi and Mayer (2004)), rehabilitation applications also need to be aware of patients' movements. This particular context presents challenges that justify an accurate and flexible underlying technology: patients have different capabilities and their rehabilitation schemes are also diverse; improvements can go from weeks to years and changes can be hardly observed by a human. It is relevant to notice that although some of the presented projects try to replace professionals, we believe that they are both an essential and irreplaceable component in physical therapy. Additionally, these systems do not provide patient-oriented therapy, and may indeed harm subjects if exercises are not performed correctly. Therefore, rather than substituting physical therapists, technology should be used as a tool for clinicians and, consequently, to improve current rehabilitation procedures.

4 Computer Assisted Virtual Rehabilitation

The analysis performed on the current rehabilitation procedures pointed out several flaws and limitations concerning both the immediate feedback and afterwards when a thorough analysis or comparison is required. To overcome the aforementioned issues, we have developed a computer-assisted virtual rehabilitation platform considering the following requirements:

Data Persistence All data must be persistent and coherent, so they can be visualized afterwards and shared by physiotherapists;

Motion Capture It should be possible to record the motion performed for retrospective data analysis and reproduction;

Accuracy The platform should enable accurate and precise recording of a particular motion, e.g., reach of a patient's hand;

Movement reproduction It should be possible to reproduce the motion at any time for analysis and evaluation;

Movement Comparison It should be possible to reproduce two movements in overlapping form, so they can be compared, e.g., to evaluate evolution;

Automatic Information Extraction It should be possible to enrich the view and ease the analysis with information, e.g., automatically present the distance between two points in a particular movement comparison;

Easy Setup The therapists should be able to prepare an exercise with little effort and requiring no particular technical or computer knowledge

The following sections present how we have tackled these requirements.

4.1 Tracking the Patients' Movements

To accomplish the goals and ensure that the requirements are fulfilled, our approach uses a virtual marker-based tracking system, where tracking of the movement is achieved through light-reflecting markers placed on the human body (Zhou (2008)) (Figure 2). The choice of such a system, motion capture, is mostly due to its precision. Moreover, it allows the monitoring of several different points at once, some of them directly related with each other (two points in the arm as in Figure 2), but others with indirect relations (trunk and arms). The latter enable the therapists to analyse posture or any erroneous movement produced. It

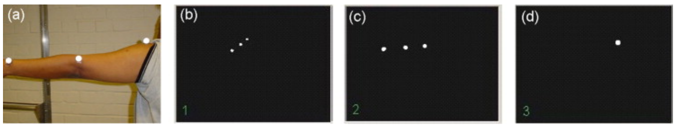

Figure 2 Virtual marker-based tracking system

is relevant to notice that although we maintain an internal notion of skeleton and where the markers are placed in the human body, we do not use rigid bodies. In other words, the markers are isolated points in space, enabling the therapists to freely select the positions to monitor.

4.2 The Therapists' Interface

Our platform enables the therapists to manage information about the patients, their sessions and keep an historical record of their exercises. Further, it enables them to compare data across sessions or even between patients. In detail, here are the most relevant features:

4.2.1 Recording a movement/exercise

The platform allows the therapist to record a movement for later visualization or comparison by choosing which points are relevant to the assessment of the movement and placing the sensors (markers) on the patient's body (Figure 4). Then, he/she is able to select them on screen and match with the desired designation (body part). This is where we create our internal skeleton representation, consisting in a set of restrictions to help the therapist visualize and compare the movement.

4.2.2 Reproducing a movement/exercise

Upon recording the movement, therapists can reproduce it, navigate and look in detail in a three-dimensional view. They are able to analyse in detail the points, and observe amplitudes and angles between joints. This function behaves like a media player where one can pause, play or even speed up/down a movement (Figure 3).

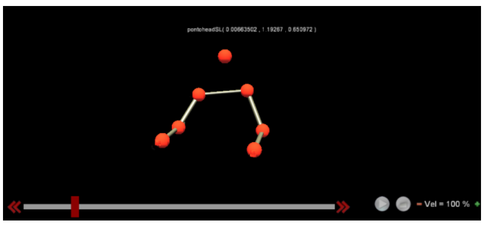

Figure 3 Movement reproduction

4.2.3 Comparing movements

At any time, therapists can select more than one movement and compare them. To ease the comparison, skeletons are overlapped and different timelines are available. This enables manual control over the different movement reproductions. We are currently working on automatic synchronization to help therapists in finding a good comparison starting point.

5 Evaluation

Physical rehabilitation is a long accompaniment process, which requires a great deal of observation and analysis from therapists. However, they do not possess the tools to perform these tasks properly. Current procedures are limited regarding the evaluation of both patients' capabilities and progress. Therefore, we believe that a three-dimensional motion tracking-based system is a valuable addition to current rehabilitation procedures, offering therapists the tools to a more accurate analysis. In order to test our hypothesis we performed an evaluation with the target population, which will be described in the next sections.

5.1 Research Questions

This evaluation aims to answer several research questions regarding our approach and software platform:

1. Is our platform useful for physical therapists?
2. Is the evaluation more accurate?
3. Are therapists able to detect the patients' progress?
4. Would therapists use the system in their rehabilitation facilities?

5.2 Participants

Since our goal was to develop a computational tool to help physical therapists in current rehabilitation procedures, subjects were recruited from different rehabilitation centers. Three therapists agreed to participate in our research. All subjects were female with ages between 22 and 35 years old. Regarding expertise, one of the participants is an intern physiotherapist while the other two have worked for more than 4 years in rehabilitation. In this evaluation we were particularly interested in analysing the benefits and limitations of our platform regarding the support that it could offer to therapists when evaluating several different movements. Because motor impaired patients may not possess the required capabilities, all movements were simulated by an able-bodied participant, which gave us more flexibility when choosing the exercises to thoroughly evaluate our system (Figure 4).

Figure 4 Patient (actor) during evaluation.

5.3 Apparatus

The evaluation was performed in a laboratorial setting featuring a motion capture system equipped with ten infra-red cameras from OptiTrack[1] that was able to track up to 12 markers placed on the patient's body. Our virtual reality rehabilitation platform was developed in C++ using Open5 Framework[2]. The evaluation was video recorded by 2 cameras and all interactions with the software were logged for later analysis.

5.4 Procedure

At the beginning of the evaluation participants were told that the overall purpose of the study was to identify the benefits and limitations of our computer platform when compared to current rehabilitation procedures. We then conducted a questionnaire in order to collect information about each participant. Subjects were then informed about the evaluation procedure. We performed 3 sessions (3 days with a day between each) with all participants in a controlled and quiet environment. In each session participants had to observe the movements and answer an evaluation questionnaire. The observation had two conditions: with or without our platform. In each session one of the participants used our platform while the remaining observed the movements without any aid. The latter were free to walk around the patient. At the end of the session, therapists were encouraged to discuss their evaluations in order to highlight the differences between the two conditions (i.e. with and without our platform). On the second and third sessions participants also had to compare the patient's performance with the last session, indicating whether the performance was worse, better or equal. In all discussions video recordings were used as a disambiguation tool. The participant that used our platform also had an additional task, which was evaluated as well: placing the markers on the patient's body and configuring the motion tracking system. The configuration consisted of assigning all markers to a point in the virtual skeleton. This process was previously explained to all participants and demonstrated by the evaluation monitor. The movements performed by our patient were chosen based on current rehabilitation practices (Figure 5): shoulder elevation on the horizontal plane with the palm facing down; shoulder elevation on the horizontal plane with the palm facing up; and hyper-extension of the shoulder with the palm

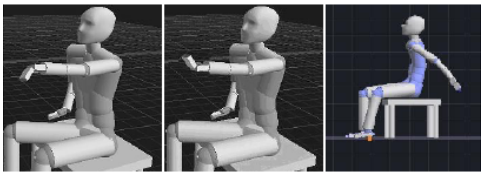

Figure 5 Movements (from left to right): shoulder elevation with the palm facing down; shoulder elevation with the palm facing up; hyper-extension of the shoulder.

facing up; We selected movements in a random order to avoid bias associated with experience. After observing each movement, the participants had to fill the evaluation questionnaire composed by questions that are usually answered in the end of a rehabilitation session: 1) Did the patient keep the back straight during the movement?; 2) What is the movement's angle?; 3) Did the patient move his head during the exercise?; 4) Did the patient move his pelvis during the exercise?; 5) Was the movement uniform?; 6) Was the movement smooth?

5.5 Results

Due to the limited number of participants, our goal is not to statistically analyse the data, but rather try to understand the potentialities and limitations of our platform and how it could be incorporated in current rehabilitation procedures. In the following sections, we present the key results and insights of this experiment.

5.5.1 Setup

At the beginning of each movement we asked the participant who was using our platform to configure it, i.e. to place the markers on the patient's body and configure the motion tracking system. With this task we wanted to assess the time required to configure our platform so it could be used in current rehabilitation sessions. Although it only needs to be configured once per session, by forcing participants to repeat this process every time a new movement was performed, it enabled us to evaluate learning effects. Figure 6 shows the time taken by

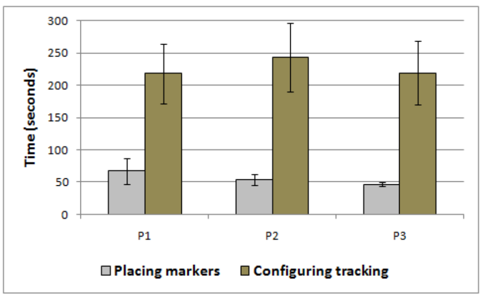

Figure 6 Mean setup times per participant

each therapist to place the markers on the patient's body and configure the tracking system. The former has shown to be very simple and easy to perform as participants knew the exact point that they wanted to observe and where each marker should be placed. After one attempt all physical therapists were able to perform this task in less than a minute. The configuration process was more time consuming, however, efficiency still increased with experience. The complete setup process requires about 5 minutes, which is relatively insignificant when considering the duration of a physiotherapy session (more than one hour). We believe that the benefits clearly compensate the time spent in this phase.

5.5.2 Accuracy

For each movement participants had to answer an evaluation questionnaire. These answers were then confirmed through video analysis, where all therapists were able to discuss and reach an agreement. Overall, participants who did not use our platform were more erroneous. For five times they could not answer correctly to questions one ("*Did the patient keep the back straight during the movement?*"), three ("*Did the patient move his head during the exercise?*") or four ("*Did the patient move his pelvis during the exercise?*"). Even after analysing the videos, participants have had difficulties evaluating the patient's movements. As video cameras were in fixed positions, it was sometimes difficult to properly observe the desired body part. On the other hand, participants using our platform were always able to correctly evaluate all movements. Since our visualization platform presents a 3D scene, participants could easily adjust their view to the most convenient position during the patient's movement. Moreover, they could retrieve crucial information in real time, such as the angle between two segments of the skeleton or the distance between two points, thus allowing a more detailed and accurate analysis of the exercise (e.g. if the patient maintained his posture).

5.5.3 Coherence

Evaluating the patients' progress, particularly when differences are only visible in the long run, is a hard task for physical therapists. Moreover, patients can be sometimes accompanied, and thus evaluated, by several clinicians, which means that this analysis is even more difficult as evaluations are very subjective and inaccurate. Therefore, we also wanted to analyse how our platform performed when the patient's progress has to be evaluated by two different therapists. In our evaluation, as in traditional rehabilitation procedures, physical therapists only shared their evaluation questionnaires of previous sessions. Then participants had to judge if the movement was better, worse or equal for each of the five evaluation questions. Participants that did not used our platform, once again, were less accurate, and unable to correctly judge the patient's progress on five circumstances (i.e. questions). Main difficulties arose in analysing the movements' angle and the patient's posture. On the other hand, our rehabilitation platform was able to support an accurate evaluation, since participants correctly evaluated the patient's progress. Through our movement comparison feature (Figure 7), therapists were able to observe how the patient performed on both sessions using objective and exact measures, thus allowing them to easily highlight the main differences.

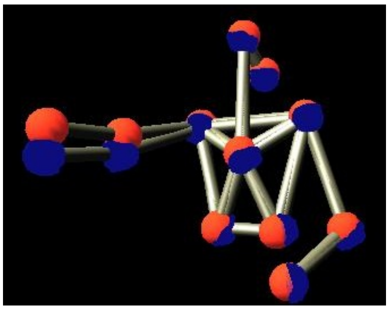

Figure 7 Movement comparison

5.5.4 Participants' Opinions

At the end of this study we gathered the participants' opinions (using a 5-point Likert scale) about our computer platform. As shown in Figure 8, participants were satisfied with the platform's accuracy. Also, they stated that placing the markers on the patient's body can be performed easily and quickly. Considering the time required configuring the tracking system opinions were less conclusive. Overall, participants stated that this computer platform would be a valuable addition to the current rehabilitation procedures and were willing to use it.

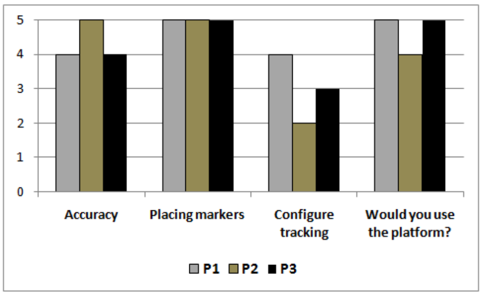

Figure 8 Participants' opinions

6 Discussion

We are now able to answer the research questions posed at the beginning of the evaluation.

Is our platform useful for physical therapists? Our platform has shown to be a valuable resource to physical therapists. Participants are able to visualize important information and adjust their point of view in real-time while patients perform their movements and exercises. Moreover, therapists can choose to reproduce the same movement and conduct a more detailed analysis. One of the most useful features was the ability to compare different movements. By overlapping them, our system allows therapists to evaluate the patients' progress while offering a useful communication platform with objective and quantitative measures. Therefore, patients can be accompanied by different therapists without any loss of quality in their evaluation.

Is the evaluation more accurate? When therapists did not use our rehabilitation platform, they had some difficulties answering the evaluation questions. Indeed, participants in this condition made more errors and were less precise. Our system allowed therapists to perform a more accurate and detailed evaluation of patient's movements.

Are therapists able to detect the patients' progress? Since our platform recorded all patient movements it was easy for the therapists to detect progresses by comparing the same movement on two different sessions. Overlapping the recorded movements allowed the participants to compare them and identify the main differences. Although the patient was not motor impaired, the tracking system is accurate enough to allow physical therapists to identify other movement variations.

Would therapists use the system on their rehabilitation facilities? Regarding participants' opinions and comments, they considered this rehabilitation platform as a valuable and accurate tool to support physical therapy. Moreover, all participants stated that they would use such a tool in their current rehabilitation procedures, which demonstrates its full potential and usefulness.

7 Conclusions

A task analysis on the rehabilitation procedure and on how therapists observe and evaluate status and evolution of their patients has been presented. The current process is limited concerning the accurate evaluation of the patients' capabilities and evolution patterns. We presented a virtual tracking-based platform that enables the therapists to have both immediate and recallable detailed information about the patients' motions, evolution and overall rehabilitation history. An evaluation with physical therapists over three sessions suggests that our rehabilitation platform is an accurate, useful and valuable addition to current rehabilitation procedures.

7.1 Future Work

Although the results obtained in this work are promising, the next stage of our research includes the deployment of our technological solution on a rehabilitation centre. Only then we will be able to perform a long-term evaluation with the main stakeholders, i.e. patients and therapists, within real rehabilitation sessions, and accurately describe the system's limitations and potential. Moreover, we will be able to compare and analyse the gain of both therapists and patients when using this solution.

Even though our research focus has been in providing a visualization tool to assist physical therapists in their work, we also intend to explore the usage of this tool to inform patients about their performance. Our goal is to diagnose the patients' motor limitations and provide appropriate feedback regarding the correctness of their movements. Furthermore, we intend to use this information to improve their engagement and motor recovery. For instance, through games that reward accurate motion patterns, thus encouraging patients to perform exercises correctly.

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