Computer-Assisted Rehabilitation

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Abstract: Recent decades brought technological advances able to improve the life quality of people with disabilities. However, practical developments are still scarce to what tetraplegics and their Rehabilitation is concerned. Therapeutic processes are lengthy and require great dedication from both the therapist and the patient. They consist in carrying out repetitive movement patterns across sessions, giving relevance to a suitable observation and accompaniment process. Our goal is to provide a system with accurate monitoring and evolution analysis assisting therapists in current rehabilitation procedures. We analyzed therapy sessions with tetraplegic patients to better understand the rehabilitation process and highlight the major requirements for a technology-enhanced tool. We then developed a prototype able to automate and improve the current monitoring and follow-up processes. Results indicate that computational movement analysis and comparison can improve the quality of a rehabilitation session and overall patient evolution analysis. The capture and virtual playback of motion in physical therapy sessions increases therapist awareness of patient condition and evolution.

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

1 Introduction

Physical therapy is one of the most relevant therapeutic processes to patients recovering from a spinal cord injury. Its main goal is to restore some quality of life to patients, through the training of movements and reactions, thus ensuring a greater independence and control of their body. However, rehabilitation is always a long, arduous and tedious process, since patients have to repeat the same exercises innumerable times and the progress is usually very slow, taking months or even years until visible changes occur.

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 the therapist and the patient. Also, they consist in carrying out repetitive movement patterns across sessions, giving relevance to a suitable observation, analysis and accompaniment process.

This research aims to develop the tools at the therapists reach and hence improve the overall rehabilitation process. To this end, we studied the daily routines, session and analysis procedures at a rehabilitation centre (Figure 1), and contribute with a set of limitations and requirements for a technologic-enhanced rehabilitation solution for therapists. Our aim is to provide physical therapists with 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 posterior analysis; have a precise and objective measure of the patients and their evolution; and being 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 therapy and rehabilitation centre. Further, building on the requirements retrieved from the aforementioned analysis, we present a virtual rehabilitation platform and the results from its evaluation with the target population.

2 Related Work

Since the main goal of this research is to develop a platform to help clinicians to monitor and evaluate the patients’ movements, we are faced with the need to be aware of the patient’s body and posture while performing their rehabilitation exercises. This leads us to tracking-based solutions.

A great deal of work has been done in tracking technologies (Zhou (2008)), which consequently allowed the development of computational rehabilitation systems. Non-visual based tracking systems have been commonly used in medicine as they are a cost effective solution and do not suffer from the “line-of- sight” problem. However, motion sensors, such as accelerometers, are inaccurate regarding position, velocity, and orientation estimation due to noise effects. Therefore, they are typically used for ambulatory health monitoring (Jovanov et al. (2005); Najafi et al. (2002)), rather than accurate movement analysis. On the other hand, visual marker tracking systems, offer accurate information position (errors are around 1mm). Cameras are applied to track movements, with identifiers placed upon the human body. Due to its accuracy, this technique allows a detailed analysis of human motion. For instance, Kejonen et al. (2003) evaluated the relationship between body-balancing movements and anthropometric characteristics of patients. Esquinazi and Mayer (2004) reported an assessment study of muscle overactivity and spasticity with motion analysis for treatment and rehabilitation planning. Further, Davis et al. used VICON, a visual marker tracking system, for gait analysis (Davis et al. (1991)). The authors were also able to calculate joint centers and segment orientations by optimizing skeletal parameters.

Marker-free visual tracking systems, although less accurate than their marker-based counterparts, have also been applied to rehabilitation practice, particularly in stroke rehabilitation (Jack et al. (2001); Zhang et al.
To better understand the rehabilitation process we carried out a 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 on tetraplegic patients as the duration of the therapy may extend for several months and, in most cases, years. This time span demands a good analysis, storage and follow-up process.

3 A Glimpse on Current Procedures

Figure 1: Traditional Rehabilitation

We performed the task analysis with 3 physiotherapists and 7 tetraplegic patients. It consisted on interviews and questionnaires to all the interventient parts, and a thorough observation of therapy exercises. The interviews were performed after the sessions to understand the goals, limitations and difficulties of each method. 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 wrong 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 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 distance to an 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 patterns, analysis and cross-movement analysis; for patients as it may increase the motivation to achieve the proper movement, as they may have feedback on their status.

4 Computer Assisted Virtual Rehabilitation

The analysis performed to the current rehabilitation procedures pointed out several flaws and limitations concerning 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 it can be visualized afterwards and shared by physiotherapists;

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

Accuracy The platform should enable accurate and precise notion 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 of the movement;

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

Automatic Information Extraction It should be able 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 no particular technical computer-wise expertise.

The following sections present how we have tackled these requirements.

4.1 Tracking the Patients’ Movements

To accomplish the goals and assure 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).

**Figure 2 Virtual marker-based tracking system**

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 analyze posture or any erroneous movement produced.

It 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.

To identify and be constantly aware of a particular point and its relation to others, even when their trajectories are crossed, we use Kalman Filters (Welch and Bishop (1995)). The Kalman filter assumes that the probability density function at each instant of time follows a Gaussian distribution. This filter allows the system’s state estimation if certain restrictions are met: if the noise has a Gaussian distribution known parameters and if the state transition represented by the system’s model is linear (that is the case) (Welch and Bishop (1995); Arulampalam et al. (2002)).

The Kalman filter has two distinct phases: Predict and Update. The predict phase uses the state estimate from the previous step to produce an estimate of the state at the current step. In the update phase, the current "a priori" prediction is combined with current observation information to refine the state estimate. However, this value is not enough to identify all the received points. To achieve this goal, we used the Mahalanobis distance (Pinho et al. (2005)) and determined which of the measured points is the closest to the calculated prediction. This process is repeated every step, with the new estimate positions and their covariance, informing the prediction used in the following iteration.

**Figure 3 Application main menu**

4.2 The Therapists’ Interface

Our platform enables the therapists to manage information about the patients, their sessions and keep an historic of their exercises (Figure 3). 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 both choosing which points are relevant to the assessment of the movement and placing the sensors (markers) on the patient’s body (Figure 5). Then, he/she is able to select them onscreen and match with the desired designation (body part). This is where we create our internal skeleton representation, a set of restrictions to help the therapist visualize and compare the movement.

4.2.2 Reproducing a movement/exercise

The platform enables the therapists to manage information about the patients, their sessions and keep an historic of their exercises (Figure 3). Further, it enables them to compare data across sessions or even between patients. In detail, here are the most relevant features:
Upon recording the movement, the therapists can reproduce it, navigate and look in detail in a three-dimensional view. They are able to analyze in detail the points, and observe amplitudes and angles between joints. This function behaves like a media player where you can pause, play or even speed up/down a movement (Figure 4).

![Figure 4 Movement reproduction](image)

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 the therapists 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 on 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 centres. 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 work for more than 4 years in rehabilitation.

In this evaluation we were particularly interested in analyzing the benefits and limitations of our platform regarding the support that it could offer to therapists when evaluating different movements. Because tetraplegic 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 (Figure 5).

5.3 Apparatus
The evaluation was performed in a laboratorial setting featuring a motion capture system equipped with ten infrared 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 posterior 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 characterize each participant. Subjects were then informed about the evaluation procedure.

We performed 3 sessions (3 days with a day in between) with all participants in a controlled and quiet environment. On each session participants had to observe the movements and answer an evaluation questionnaire. The observation had two conditions: with or without our platform. On 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. In 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 if 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 in assigning...
all markers to a point in the virtual skeleton. This process was previously explained to all participants and demonstrated by the evaluation monitor.

Figure 6 Movements (from left to right): shoulder elevation with the palm facing down; shoulder elevation with the palm facing up; hyperextension of the shoulder.

The movements performed by our patient were chosen based on current rehabilitation practices (Figure 6): shoulder elevation on the horizontal plane with the palm facing down; shoulder elevation on the horizontal plane with the palm facing up; and hyperextension of the shoulder with the palm 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 analyze 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 7 shows the time taken by each therapist to place the markers on the patient’s body and configure the tracking system. The former has show 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 try 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 come to an agreement.

Overall, participants that did not use our platform were more erroneous. For five times they could not answer correctly to questions one (“Did the patient kept 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 analyzing the videos, participants have shown difficulties evaluating the patient’s movements. As video cameras were on a fixed position, 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 on 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 analyze 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 use our platform, once again, were less accurate, and unable to correctly judge the patient’s progress on five circumstances (i.e. questions).
Main difficulties consisted in analyzing the movements’ angle and the patient’s posture.

**Figure 8 Movement comparison**

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 8), 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.

5.5.4 Participants’ Opinions

At the end of this study we gather the participants’ opinions (using a 5-point Likert scale) about our computer platform. As shown in Figure 9, participants were satisfied with the platforms’ accuracy. Also, they stated that placing the markers on the patients’ body can be performed easily and quickly. Considering the time required to configure 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 9 Participants’ opinions**

6 Discussion

We are now able to answer the research questions proposed 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.

Nevertheless, one of the most useful features was movements’ comparison. By overlapping movements, our rehabilitation platform 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 the 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 his progresses by comparing the same movement on two different sessions. Overlapping the recorded movements allows the participants to compare them and identify the main differences. Although the patient was not tetraplegic, our tracking system is accurate enough to allow physical therapists to identify small 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 and Future Work

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 immediate and on-recall detailed information about the patients’ motions, evolution and overall history. An evaluation with physical therapists over three sessions showed that our rehabilitation platform is an accurate, useful and valuable addition to current rehabilitation procedures.

Future work includes developing new techniques to enhance the platform’s setup, deployment on a rehabilitation centre, and using the information retrieved from the system to improve the process on the patient’s end, e.g., rehabilitation games.

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**References**


