# BACKTRAINER
## *Computer-aided Therapy System with Augmented Feedback for the Lower Back*

Dominique Brodbeck, Markus Degen, Michael Stanimirov
*School of Life Sciences, University of Applied Sciences Northwestern Switzerland, Muttenz, Switzerland*

Jan Kool[1], Mandy Scheermesser[1], Peter Oesch[2], Cornelia Neuhaus[3]
[1]*Department of Health, Zurich University of Applied Sciences, Winterthur, Switzerland*
[2]*Clinic Valens, Center for rehabilitation, Valens, Switzerland*
[3]*University Children's Hospital UKBB Basel, Basel, Switzerland*

Keywords: Back pain, Physiotherapy, Computer-aided therapy, Augmented feedback, Ambient visualization.

Abstract: Low back pain is an important problem in industrialized countries. Two key factors limit the effectiveness of physiotherapy: low compliance of patients with repetitive movement exercises, and inadequate awareness of patients of their own posture. The Backtrainer system addresses these problems by real-time monitoring of the spine position, by providing a framework for most common physiotherapy exercises for the low back, and by providing feedback to patients in a motivating way. A minimal sensor configuration was identified as two inertial sensors that measure the orientation of the lower back at two points with three degrees of freedom. The software was designed as a flexible platform to experiment with different hardware, and with various feedback modalities. Basic exercises for two types of movements are provided: mobilizing and stabilizing. We developed visual feedback - abstract as well as in the form of a virtual reality game - and complemented the on-screen graphics with an ambient feedback device. The system was evaluated during five weeks in a rehabilitation clinic with 26 patients and 15 physiotherapists. Subjective satisfaction of subjects was good, and we interpret the results as encouraging indication for the adoption of such a therapy support system by both patients and therapists.

## 1 INTRODUCTION

Low back pain (LBP) is a very frequent condition in industrialized countries leading to high burden to the health care system (van Tulder and Koes, 2002; van Tulder and Koes, 1995). In the majority of cases, no patho-anatomical causes for the complaints are present and they are classified as non-specific LBP (Deyo and Weinstein, 2001). Active and supervised movement exercises are effective in reducing pain and restoring function in non-specific LBP (Abenhaim L., e. a. 2000; Hayden et al., 2005). However, there are several factors that limit the effectiveness of such exercises and lead to poor therapy outcomes:

- proprioception is inadequate for the lumbar spine
- movement exercises are difficult to learn
- exercises require a lot of repetition to be effective
- appropriate feedback requires continuous presence of a physical therapist

Thus, the main problems are insufficient patient motivation to comply with exercise regimes, as well as the inability of the patients to exercise independently. The aim of the Backtrainer project is to address these limitations of current conservative therapy, by automatically monitoring movement exercises in real time, generating a motivating, game-like visual feedback, and storing patients' performance data for later assessment.

The system has to be easy to use and simple enough, in order for it to be adopted by physical therapists, and so that it can be used by patients at home. Although monitoring of back movements and postures in laboratory settings, but also at the workplace, has gained a lot of attention in the past, there are no technical solutions available that would fulfill these requirements.

This leads to the following research questions:

- What is a minimal sensor configuration that still produces enough data, in order to generate valid feedback for movement exercises?



Brodbeck D., Degen M., Stanimirov M., Kool J., Scheermesser M., Oesch P. and Neuhaus C. (2009).
BACKTRAINER - Computer-aided Therapy System with Augmented Feedback for the Lower Back.
In *Proceedings of the International Conference on Health Informatics*, pages 66-73
DOI: 10.5220/0001550400660073

- What basic set of exercises needs to be supported by the software to cover most common therapy needs?
- In what form can the software provide intuitive feedback about posture to focus patients' attention on the aspects that are relevant for the task?
- How can the software motivate patients to use the system?

The problem was approached in three steps: (i) identify the minimal sensor configuration, (ii) build a prototype system, and (iii) evaluate the system in a controlled clinical setting.

## 2 BACKGROUND

There have been numerous research projects addressing the measurement of the kinematics of the spine. High-end systems usually use optical sensors, with either passive or active markers that are glued onto the skin. These systems have a very high precision, often in the sub-millimeter range, and are used by the video-game and movie industry for motion capturing and animation generation. Other measurement setups consist of sensors based on ultrasonic waves to measure distances, electro magnetic tracking systems (Van Herp et al., 2000; Jordan, 2001), resistance strain gauges, optical fibres (Dunne et al., 2006), or sensors that use a combination of accelerometer, compass, and gyroscope to determine the orientation of the sensor (Lee and Laprade, 2003).

Each sensor technology has its advantages but also its drawbacks. Optical systems can often capture only in a small area, and there must be an unobstructed line of sight from the camera to the markers. Systems based on electromagnetism can be influenced by the environment (i.e. training machines built of iron or steel).

Research has also been done to compare the accuracy of skin mounted (glued) sensors with radiographs or magnetic resonance imaging used to identify the actual positions of vertebrae (Yang et al., 2005; Mrl and Blickhan, 2006). The results show that positions and motions of the skin markers can be used as an estimate for the calculation of the position and orientation of the underlying vertebrae. It should also be noted that the goal of our system is not diagnosis, but to support physiotherapists whose work is also based on surface observations.

Some recent publications focus on camera based systems. In (Engels and Leloup, 2006) a system based on low cost cameras has been described. This system works with infrared cameras and a headband, with mounted reflectors that can be used to recognize and identify different sitting postures. Although the low cost camera approach seems promising, it is not applicable in our situation because of the line of sight problem, which applies to other optical systems as well.

The therapy system that was proposed in (Sucar et al., 2008) also uses cameras to track gestures from stroke patients and, in addition, provides augmented feedback in a game-like setup. Another promising approach, using multi-modal feedback in neural rehabilitation, is described in (Huang et al., 2005). This system uses visual as well as auditory means for feedback on functional, task-oriented exercises.

## 3 IDENTIFICATION OF SENSOR CONFIGURATION

In order to satisfy the requirement of a simple and easy to handle system, we had to identify the minimal configuration of sensors that would still produce enough data in order to classify movement quality and performance, and to generate valid feedback. The hypothesis was that it is sufficient to measure the orientation of the lumbar spine at two points with three degrees of freedom.

We used an optical motion capturing system (Optotrak Certus from NDI) with 22 infrared LEDs positioned on the subjects' back (see Figure 1). The precision of this system is in the sub-millimeter range, and data was collected with a sampling rate of 30 Hertz. In addition to the telemetry data, we captured the movement of the subjects on video at a rate of 15 frames per second. This provided us with a setup that is sufficiently overdetermined, to allow us to simulate and virtually evaluate many different potential sensor configurations.

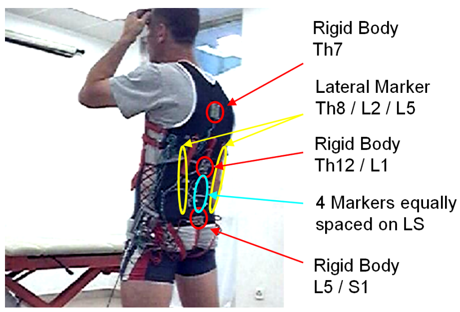


Figure 1: 22 markers were positioned in the region of the lumbar spine (LS), and tracked with a high-precision optical motion capturing system, in order to analyze the motion of the lower back during standard movement tasks.

Then we identified a set of movement tasks that are commonly used for the management or in the diagnosis of low back pain:

1. Posture Correction (while seated)
2. Range of Motion (flexion/extension)
3. Range of Motion (lateral flexion)
4. Range of Motion (rotation)
5. Stabilization of lumbar spine during knee extension
6. Lifting test (light load: 7.5 kg)
7. Lifting test (heavy load: 7.5-45 kg individually)

We recruited 22 healthy subjects between the ages of 18 to 55 years, and asked them to perform the above sequence of tasks. This produced a total of 2.4 hours of video synchronized with 5.6 million 3D positions for all of the markers. Standard statistical tools are too limited to explore and analyze this large body of information. We therefore developed a highly interactive visualization application that would allow us to visually explore the data, and experiment with different scenarios.

The visualization application consists of multiple coordinated views that simultaneously show:

- x, y, z positions of all the markers projected onto the three planes of the body (sagittal, coronal, transversal)
- 3D view of the marker positions in space
- synchronized video frames
- missing values (due to line of sight problems)
- derived values (e.g. spatial angles between pairs of markers, distances)

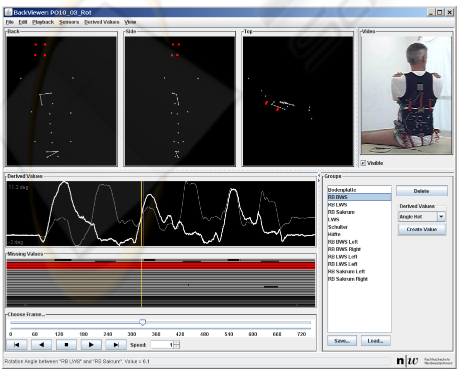

Figure 2: The interactive visualization application uses multiple coordinated views to show different aspects, in order to explore and analyze all the data that was recorded.

The software allows to plug in any number of algorithms that produce derived values from selected marker positions. We developed algorithms to measure angles and distances, as well as various projection methods onto the body planes. The videos were examined visually by physiotherapy experts, and marked up at points in time where subjects lost their ability to stabilize the lumbar spine during the exercises.

This analysis revealed the following results:

- The shape of the lumbar spine can be quantified by measuring the angle between vertebrae Th12/L1 and L5/S1.
- The difference between correct, stable movements and unstable, potentially dangerous movements can be identified in the data, and corresponds to visual assessment by physical therapists.
- The necessary data to evaluate the quality of movement can be acquired by the use of skin surface sensors.

Based on these results we confirmed our hypothesis that for our intended goal to support therapy of low back pain, it is sufficient to measure the orientation of the lumbar spine at two points, with three degrees of freedom.

# 4 THE BACKTRAINER SYSTEM

## 4.1 System Overview

The Backtrainer prototype consists of two inertial sensor modules, capable of measuring the three rotational degrees of freedom. Each of the two modules is positioned on the patients' back using an elastic band (Figure 8). Motion data from the two sensor modules are transmitted to a PC.

On the PC, a therapy software receives the signals and reconstructs the movements of the lumbar spine. The software further consists of a patient database, and a set of movement exercises that can be configured for the individual patient. The software supports the therapist in instructing complex movements, and allows the patient to exercise independently in a motivating, game-like environment, and document therapy activities and progress.

Figure 3 shows an architectural overview of all components of the system.

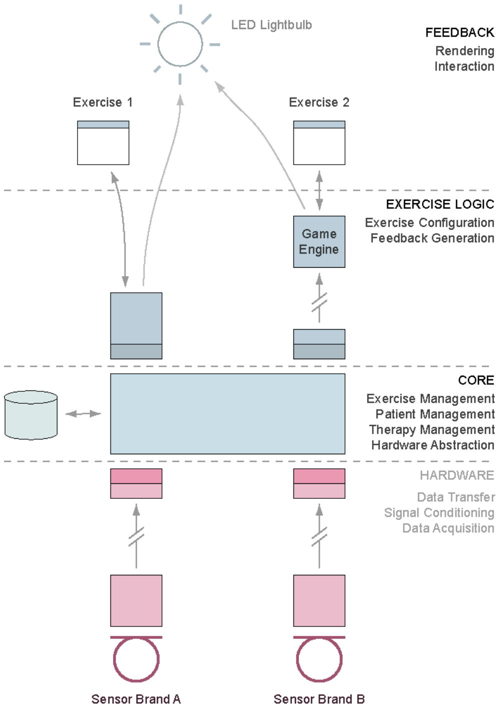


Figure 3: Overview of the Backtrainer system. Hardware, exercise logic, and feedback are abstracted into separate layers to guarantee high flexibility and extensibility.

## 4.2 Inertial Sensors

Of the sensing technologies discussed in section 2, we chose to use inertial sensors, because of their low cost and simplicity of use. We first considered to develop a sensor based on accelerometers, gyroscopes, and magnetometers on our own, but recently, many commercial sensors of this type that match our specifications have become available, and therefore we decided against it.

We used sensors from two different manufacturers. One was a wireless system (InertiaCube3 from Intersense), and another one was a system where the sensors are connected to the PC with USB cables (MotionNode from GLI Interactive). We abstracted the interfacing of the sensors in the software, so that we are able to switch systems easily.

## 4.3 Software

The software is separated into several layers to guarantee high flexibility and extensibility (Figure 3). The core application layer is responsible for the hardware abstraction, as well as basic patient, exercise and therapy management. The exercises are abstracted into a separate layer, which makes it possible to easily add any number of exercises to the system. This exercise logic layer takes care of configuration, generation of feedback, and determination of the exercise success level. Rendering and interaction are done in the feedback layer, to support the use of different feedback modalities.

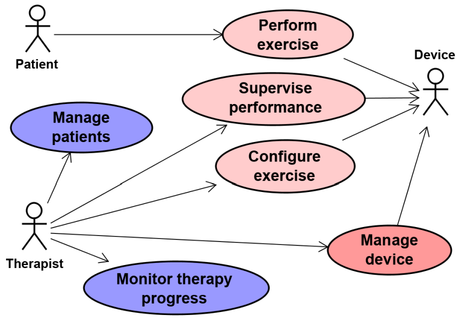


Figure 4: Use cases resulting from the task analysis.

In order to design the user interaction, a task analysis was performed based on scenarios of future therapy sessions. The resulting use cases are summarized in Figure 4.

Analysis of the use cases and iterative prototyping together with therapists, lead to three areas of interaction that were then implemented in the following main screens:

**Device:** Management of the hardware (Initialization, calibration, monitoring).

**Personae:** Management and selection of therapist and patients, monitor therapy (exercise performances, access to historical data).

**Exercises:** Selection and performance of exercises (configuration, personalization, feedback).

These three screens reproduce the main work flow executed in a therapy session:

1. Initialize the device and make sure the sensors are mounted correctly and deliver signals.
2. Select therapist and patient, review previous sessions and decide on the exercises to be performed in the current session.
3. Select, perform and evaluate exercises.

## 4.4 Exercises

The exercises are the main concept within the Backtrainer system, they target the training area and can be divided into the two groups of mobilizing and stabilizing exercises.

### Mobilization Exercises

The aim of mobilization exercises is to restore the range of motion of the patient. The physiotherapist, together with the patient, set range limits which enclose the required movement range to achieve the treatment goal. This range is visualized to the patient by a white ball moving within the predefined range limits. The ball turns its color to green if the wanted limits are reached and to red if these are exceeded. This information assures him/her that motions within this range will be most effective. This is important, because it prevents patients to be overcautious or overambitious, which would result in a lower success rate of the therapy. The success level of a particular performance of the mobilizing exercise is defined as the ratio of number of times that the limit was reached to the total number of attempts.

Figure 5 shows the application window with the mobilizing exercise selected. The slider and buttons on the right allow the adjustment of exercise parameters.

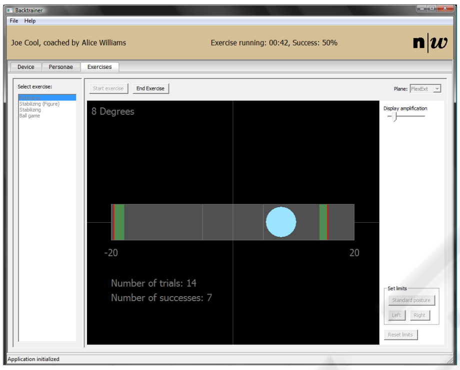


Figure 5: Mobilizing feedback.

### Stabilization Exercises

The goal of stabilization exercises is to hold the lumbar spine in a given stable position, while performing movements such as ”squats”, lifting weight, or changing from sitting to standing. For this type of exercise, it is important to provide the patient with an augmented feedback of the posture of the lumbar spine, as proprioception of this region is typically low.

The metaphor of a ”green range” was introduced, meaning that motions within this range are perfectly tolerable. This range is adjustable and allows to define the level of difficulty for the exercise.

Our first approach for the visualization of the lumbar spine posture used a comic like stick figure that had a bendable spine. Tests showed however that this approach worked only, if the subject was positioned exactly as the figure on the screen (i.e. standing upright). In other situations (e.g. sitting, kneeling), this concrete depiction turned out to be more confusing than helpful.

We therefore replaced the figure by a more abstract visualization of a sphere balancing on a curved convex surface. Figure 6 shows these two approaches side by side. When the patient leaves the ”green range”, then the ball slides down on one side of the surface, and changes its color from yellow gradually to red, depending on how much the current measured angle is away from the green angle.

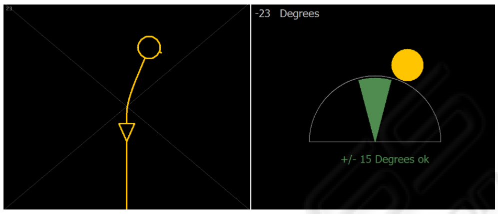


Figure 6: Stabilizing feedback: The first version (left) used a figure like feedback but was then replaced by a more abstract visualization using a ball balanced on a bump.

### Game Exercise

As described in section 1, movement exercises with many repetitions are key to therapy effectiveness. Patient compliance with repetitive movement exercise regimes is problematic though. We developed a simple game with the aim of enhancing motivation and compliance.

In the game, the patient controls a bat at the bottom of the window (Figure 7). The bat can be moved from left to right, according to the difference in rotational angles between the upper and lower sensor modules. Which of the three rotational planes should be used for the mapping, can be freely chosen by the therapist, depending on the therapy goal. The task in this game is to catch the balls that are rolling from the back toward the front at randomly chosen offsets from the center line. The ratio of caught vs. missed balls is displayed as a score, and the final score is recorded as the success level of this exercise in the patients' therapy history.

This simple game is implemented in the Backtrainer software using basic ”OpenGL” commands,

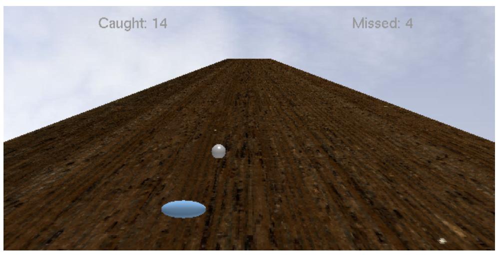


Figure 7: Game feedback: A ball (grey) is rolling from the back toward the player and has to be caught by a bat (blue).

but the software design explicitly addresses the possibility to integrate more sophisticated games that can be based on so called game-engines (Figure 3). Game engines facilitate the implementation of 3D games providing elaborate functions for the realization of virtual worlds, avatars and leveling systems.

**Lightbulb Feedback**

The movements that a patient executes while performing a movement exercise often involve a rotation of the line of vision of the patient (e.g. rotation of the upper body in the coronal plane), or the line of vision is not oriented horizontally (e.g. patient lying on the chest). In such situations, it is unpractical to provide a visual feedback on a computer screen with a fixed position. It would be helpful to provide feedback that is not directional in nature, but embedded in the environment in an ambient way.

Auditory feedback is one possibility. However, physiotherapy for low back patients is often performed in clinical therapy settings, where many patients exercise in the same room at the same time. In such a setting, auditory feedback can be distracting and confusing.

Research in the field of human computer interaction suggests the use of ”ambient displays”. Ambient displays are abstract, peripheral displays that visualize information on the *periphery of a user's attention* (Mankoff et al., 2003). This approach can also be adapted to physiotherapy, to let the patient concentrate on the exercises and nevertheless perceive feedback about the movements.

For the Backtrainer system, we built a very simple but effective component to generate an ”ambient feedback” using a modified color changing LED Lightbulb (Figure 8). The Lightbulb was instrumented with a USB-interface in order to be able to change the color from software for any combination of the two primary colors red and green.

The Lightbulb matches the ball metaphor that is used for the feedback shown in the software on the computer screen. Some exercises can be performed with only the Lightbulb feedback (e.g. stabilizing exercise) while others (e.g. game exercise) use the Lightbulb as an additional feedback modality. Apart from being an ambient feedback system for the patients, the bulb can also be used by physiotherapists coaching several patients at the same time. The therapist can observe the emitted color from a distance and intervene to adapt exercise settings, i.e. if there are too many ”misses” while playing the game exercise.

Figure 8 shows a therapy situation with the Backtrainer mounted on the patients back, the LED Lightbulb and the physiotherapist. The patient is performing a stabilizing exercise (weight lifting while stabilizing the lumbar spine).

Figure 8: The Backtrainer system in a therapy situation.

## 5 CLINICAL EVALUATION

In order to evaluate the Backtrainer system, we performed an exploratory study in a controlled clinical setting. The goal of this study was to use the system under realistic conditions, in order to evaluate the practicality in various situations. In particular the goals were:

- Evaluation of the practicality (expenditure of time, handling, ease of use) and application in a therapeutic setting.
- Evaluation of acceptance of the system by therapists and patients.
- Evaluation of the feedback produced by the system.

The study was performed in the rehabilitation clinic Valens, Switzerland. 15 physical therapists were given a short introduction to the Backtrainer system. After this introduction, the therapists were free to use the system at their discretion during their regular therapy sessions with patients that suffer from chronic back pain or that have undergone back surgery. Both, patients and therapists were asked to fill out questionnaires asking about their subjective satisfaction with the system. In addition, the software is equipped with extensive logging to provide objective data about the use of the system.

The study was planned for a duration of five weeks. We report preliminary results after 80% of this time has elapsed. The following discussion of the results focuses on those aspects that relate to the software of the Backtrainer system. In depth analysis of the overall study is subject of further research, once the study is completed.

During the period under investigation (21 days), the system has been in use between 1 and 2 hours per day. 26 patients have performed therapy sessions with the Backtrainer. They have performed a total of 248 exercises distributed as follows: mobilizing (17%), stabilizing (51%), game (32%). The average duration of an exercise was about 2 minutes with the 90% quantile at 5 minutes (8 minutes for the game exercise). Since the game exercise can be considered a mobilizing exercise, the distribution between the two types of exercises is just about half and half.

We have received filled-out questionnaires from 18 patients and 8 therapists up to this point. The numbers are not complete due to the fact that the study is still on-going, and questionnaires will typically be filled out toward the end. Nevertheless, the numbers are sufficiently large that they do provide an indication for the important trends.

Tables 1, 2, and 3 show the answers to selected questions. In general, the feedback provided by the Backtrainer is considered helpful by both patients and therapists, and it matches the visual observations of the therapists. Patients generally indicate that when training individually, it is more fun to train with the Backtrainer. We will have to further investigate into the reason for the few less favorable answers though. Therapists indicate that they can use the Backtrainer to measure therapy progress. The evaluation of the software by the therapists is favorable.

Table 1: Patient questionnaires (n = 18). Encoding: 4 Completely agree, 3 Agree somewhat, 2 Disagree somewhat, 1 Completely disagree.

| Question | Encoded Answers [# answers] 4 | 3 | 2 | 1 | Statistics $\bar{x}$ | $\sigma$ |
|---|---|---|---|---|---|---|
| Feedback from the Backtrainer was helpful | 12 | 6 | 0 | 0 | 3.7 | 0.5 |
| Feedback is easy to understand | 13 | 5 | 0 | 0 | 3.7 | 0.4 |
| Makes it easier to perform exercises on your own | 8 | 7 | 0 | 2 | 3.2 | 0.9 |
| Independent training is more fun with the Backtrainer | 8 | 7 | 2 | 1 | 3.2 | 0.9 |

Table 2: Physical therapist questionnaires (n = 8). Encoding: 4 Completely agree, 3 Agree somewhat, 2 Disagree somewhat, 1 Completely disagree.

| Question | Encoded Answers [# answers] 4 | 3 | 2 | 1 | Statistics $\bar{x}$ | $\sigma$ |
|---|---|---|---|---|---|---|
| Feedback from the Backtrainer was helpful for patients | 4 | 4 | 0 | 0 | 3.5 | 0.5 |
| The feedback matched my observations | 4 | 2 | 1 | 0 | 3.4 | 0.7 |
| It is possible to measure therapy progress with the Backtrainer | 4 | 3 | 1 | 0 | 3.4 | 0.7 |
| Patients are motivated to use it | 5 | 3 | 0 | 0 | 3.6 | 0.5 |

Table 3: Software evaluation by physical therapists (n = 8). Encoding: 4 Completely agree, 3 Agree somewhat, 2 Disagree somewhat, 1 Completely disagree.

| Question | Encoded Answers [# answers] 4 | 3 | 2 | 1 | Statistics $\bar{x}$ | $\sigma$ |
|---|---|---|---|---|---|---|
| Overall impression is very good | 0 | 8 | 0 | 0 | 3.0 | 0.0 |
| The software fulfills its task | 4 | 4 | 0 | 0 | 3.5 | 0.5 |
| The software matches my expectations and habits | 2 | 5 | 1 | 0 | 3.1 | 0.6 |

## 6 CONCLUSIONS AND FUTURE WORK

We have developed a system to support physiotherapy of low back pain. We found that this is possible by measuring the orientation of the lumbar spine at two points, with three degrees of freedom. The dynamic behavior and accuracy of commercially available inertial sensors are good enough for this application.

The layered software architecture that we developed has proven effective in integrating different hardware systems, and providing the flexibility needed for prototyping. The separation of code for the exercise concept into core, logic, and feedback is useful for providing various feedback modalities in a modular way.

The task analysis and the division of the interface into three areas, resulted in a system that was easy to use and matched the workflow of a typical therapy session. The distribution of the exercise types performed during the clinical evaluation shows that the distinction between mobilizing and stabilizing movements is fundamental and well reflected in practice.

The abstract visual feedback that we designed was considered helpful. Ambient feedback in the form of the Lightbulb proved to be a very useful addition to the computer screen in a real-life therapy setting. With regard to feedback and motivation, the study only provided some first hints though. Participants liked the game and the feedback, but there is further systematic investigation needed to answer our research questions in this area.

The usage patterns and the answers from the questionnaires from the clinical evaluation provide a stable foundation for the further development of the Backtrainer system. Since therapists did not have to follow a fixed protocol, but were free to use the Backtrainer when they saw a need, we interpret the numbers that we found as encouraging indication for the adoption of such a therapy support system.

The above results suggest future work for the elaboration of the system in several areas:

- Evaluate other feedback modalities (e.g. auditory, tactile), and other ambient devices (e.g. light emitting floor panels). Also the use of wearable 3D-Displays (Eye-goggles) will be evaluated.
- Explore a telemedical scenario in which the exercises performed by the patient at home can be evaluated by geographically distant physiotherapists to provide guidance for the patients.
- Evaluate "virtual reality" game-like feedback modalities to further raise motivational factors.

## ACKNOWLEDGEMENTS

This work was supported by funding from the Swiss Innovation Promotion Agency CTI. The authors would like to thank Hocoma AG for their support.

## REFERENCES

Abenhaim L., e. a. (2000). The role of activity in the therapeutic management of back pain: Report of the Paris International Task Force on Back Pain. *Spine,* 25(4 Suppl):1S33S.

Deyo, R. and Weinstein, J. (2001). Low back pain. *N Engl J Med,* 344(5):36370.

Dunne, L. E., Walsh, P., Smyth, B., and Caulfield, B. (2006). Design and evaluation of a wearable optical sensor for monitoring seated spinal posture. *In ISWC,* pages 6568.

Hayden J.A., M.W. van Tulder, G. T. (2005). Systematic review: strategies for using exercise therapy to improve outcomes in chronic low back pain. *Ann Intern Med,* 142(9):77685.

Huang, H., Ingalls, T., Olson, L., Ganley, K., Rikakis, T., and He, J. (2005). Interactive multimodal biofeedback for task-oriented neural rehabilitation. *Engineering in Medicine and Biology Society, 2005. IEEE-EMBS 2005. 27th Annual International Conference of the,* pages 25472550.

Jordan, K., Dziedzic, K., Mullis, R., Dawes, P. T., and Jones, P. W. (2001). The development of threedimensional range of motion measurement systems for clinical practice. *Rheumatology,* 40(10):10811084.

L. Engels, T. Leloup. T, N. W. (2006). Imaging technologies for avoiding back pain at work. In *In proceedings First Symposium of the IEEE/EMBS Benelux Chapter,* pages 235238.

Mankoff, J., Dey, A. K., Hsieh, G., Kientz, J., Lederer, S., and Ames, M. (2003). Heuristic evaluation of ambient displays. In CHI 03: *Proceedings of the SIGCHI conference on Human factors in computing systems,* pages 169176, New York, NY, USA. ACM.

Mrl F., Blickhan R. (2006). Three-dimensional relation of skin markers to lumbar vertebrae of healthy subjects in different postures measured by open MRI. *European Spine Journal,* 15(6):74251.

Raymond Y.W. Lee, Judi Laprade, E. H. F. (2003). A realtime gyroscopic system for three-dimensional measurement of lumbar spine motion. *Medical Engineering & Physics,* 16(5):817824.

Sucar, L. E., Leder, R. S., Reinkensmeyer, D. J., Hernndez, J., Azcrate, G., Casteeda, N., and Saucedo, P. (2008). Gesture therapy - a low-cost vision-based system for rehabilitation after stroke. In Azevedo, L. and Londral, A. R., editors, *HEALTHINF (2),* pages 107111. INSTICC - Institute for Systems and Technologies of Information, Control and Communication.

Van Herp, G., Rowe, P., Salter, P., and Paul, J. P. (2000). Three-dimensional lumbar spinal kinematics: a study of range of movement in 100 healthy subjects aged 20 to 60+ years. *Rheumatology, 39* (12):13371340.

van Tulder M., B. Koes, C. B. (2002). Low back pain. *Best Pract Res Clin Rheumatol,* 16(5):76175.

van Tulder M.W., B.W. Koes, L. B. (1995). A costofillness study of back pain in The Netherlands. *Pain,* 62(2):23340.

Yang, Z., Griffith, J., Leung, P., Pope, M., Sun, L., and Lee, R. (2005). The accuracy of surface measurement for motion analysis of osteoporotic thoracolumbar spine. *Engineering in Medicine and Biology Society, 2005. IEEE-EMBS 2005. 27th Annual International Conference of the,* pages 68716874.