Interactive Infrastructures – Physical Rehabilitation Modules for Pervasive Healthcare Technology

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Abstract
Traditional physical rehabilitation techniques are based mainly on mechanical structures and passive materials. This has certain limitations, which can be overcome by applying interactive technologies. As a team of designers, technologists and medical researchers and practitioners, we have developed an interactive sensor floor tile system and several other modules for rehabilitation exercises, as part of an interactive infrastructure to support rehabilitation. Since 2009, the team has advanced its understanding of rehabilitation practices and problems, and designed prototypes, interventions and demonstrators in order to gain feedback on our approach. We have identified as the three critical issues affecting rehabilitation *motivation, customisation,* and *independence.* The system that we have developed is founded on the current mechanical practices, of improvisational nature, and creative use of existing materials and techniques, expanding from this way of working by applying new interactive digital technologies and 3D instant manufacturing techniques. We have developed a number of modules for the system, and a physical programming technique which aims to blend in with current practices. Two sets of sensor floor modules are in use in hospitals and we are reporting in this chapter the first positive effects the system has on the rehabilitation of stroke patients.

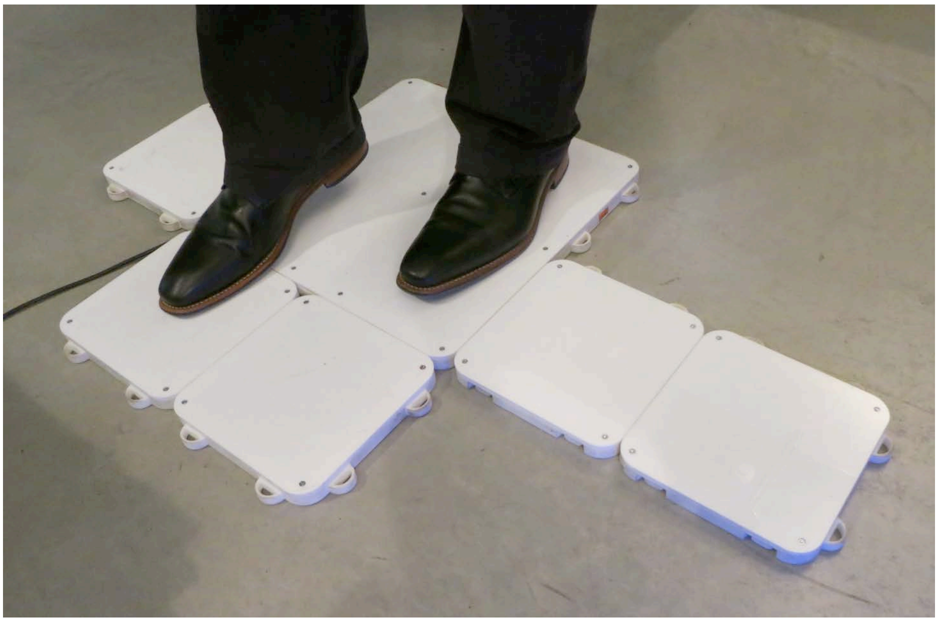

Figure 1 The Interactive Rehabilitation Tiles 3D printed modules

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Glossary

CAD - Computer Aided Design; using computer software tools to design 3D models of a shape, which can then be produced using CAM technologies (see below).

CAM Computer Aided Manufacturing; computer controller fabrication techniques, including existing techniques under computer control (such as CNC Milling, a milling machine that is under 'computer numerical control') or new techniques such as laser cutting of flat materials and 3D printing (additive manufacturing).

DoF - Degree of Freedom; a way of describing movement in 3D space, both for the lateral locations on the three axis and the rotational orientations around those three axis.

HCI - Human-Computer Interaction; the field of study into the relationships between human(s) and computer systems, applied in the field of interaction and interface design.

Interactivation - a design and research approach that encourages making things (objects, instruments and spaces) interactive. It is a means of enabling computer systems to interact with the users. through elaborate, engaging, sensitive, rich and spatial interfaces.

Introduction

Traditional physical rehabilitation exercise techniques can be enhanced through the application of interactive technologies. After studying rehabilitation practices for several years, we have identified three key areas where improvement can be achieved. These key issues are *motivation* (offering informative and rewarding feedback to the patients to support them to participate fully in the therapies), *customisation* (the ability to adapt and personalise the systems to the wide range of needs of different patients and therapies), and *independence* (enabling the patients to follow therapies away from the hospital, when and where it suits them, under remote expert guidance of the therapists and practitioners, including the highly desirable feature of automatically logging patient exercise data).
These key issues will be discussed in detail in the next section, as well as our approach for addressing the key issues by developing and applying interactive strategies. Our studies focused on staff practices in the hospital ward, and consisted of unobtrusive observations, appropriate interventions, unstructured interviews, and explicit requests for participation. In effect, our aim was to have the practitioners drive our research and developments, as is common practice in design research. Our proposals proceed from existing practices and our approach is inspired by actual therapies. The work is based on the current mechanical and often very creative solutions of physiotherapists and other practitioners. Rather than replacing their practices, we are *extending* the way physiotherapists work by applying the digital technologies.

State-of-the-Art

The first phase of the project (in 2009 and 2010) explored the rehabilitation practices of various hospitals, through observations and conversations with practitioners, and collaborations with medical researchers reported in a previous publication (Bongers and Smith, 2011). We included an overview of the rich variety of rather effective mechanical and material solutions that the therapists worked with. The focus of the earlier work was around Spinal Cord Injury (SCI) patients. They are often young adults and we therefore explored the use of video games as structured interactive environments for them to carry out their exercises. This included the modification and appropriation of existing game controllers such as the Wii-mote (extending the switches to be more easily operated by the patient) and Wii balance board (which was adapted for wheelchair use). However we found this approach was limited due to the fixed mappings between player's movements as picked up by the controllers, and the game parameters. We therefore developed our own interfaces, using 3D printing techniques and wireless sensor modules. All this work has been reported in a book chapter (Bongers and Smith, 2011) which also included an overview of the rehabilitation and medical practices.

Three key Issues

Our studies since 2009 have identified key areas (motivation, customisation, and independence) which we will discuss in this section. Each of these have specific issues and challenges, and we have identified possible improvements and solutions by using techniques of interaction with computer generated guidance and feedback, and new product design techniques.

Motivation

The first key challenge for patients and therapists is boredom or lack of motivation to continue with rehabilitation because of the repetitive nature of the tasks. We propose that the (inherent and necessary) repetitive tasks can be made more acceptable by making the tasks more entertaining and engaging by applying multimodal and multi-levelled feedback. Motivating patients is crucial in rehabilitation exercises, and often relies on the skills and enthusiasm of the therapist. From literature on motivation and social psychology (Furnham, 1997), we know that the best results come from intrinsic motivation (Calder and Staw, 1975). While a patient usually will have a strong intrinsic motivation to get better, this is a long-term goal and only achieved through slow (and often barely noticeable) progress. The skill of the therapist is to transfer, as it were, the extrinsic motivation (the patient doing the exercise for the therapist) to an intrinsic one. Appropriate feedback, as presented by our systems, can play a crucial role in this process. It can also help to present rewards in the form of feedback, to motivate their development by achieving short-term goals in pursuit of the longer term goal (Siegert and William, 2004). Another function of the enhanced feedback and information presentation of an interactive system is to educate and inform the patient about the need and reasons to perform an exercise, explaining more of the process. This can be a problem in traditional practices, and has been found to be detrimental to the patient's motivation (Maclean et al, 2000). In interactive systems it is possible to add feedback and present information using various interaction modalities, for instance using video, graphics, lights, movement, sound and music. It can possibly be part of a trophy tangible object (Bagalkot et al, 2012). This motivation support can also be more entertaining. Video games have been found to be successful in this context as a motivating environment, and are suitable when the levels of achievement and reward are matched with the therapeutic goals, which will be discussed in a section below. Although we have investigated using standard game controllers and games (such as the Nintendo Wii), we remain focused on creating flexible, custom made interfaces and environments in which we can control the link between game play and therapy. We have also found that even very plain feedback from LEDs and sound can enhance therapy and motivate patients.

Customisation

From our research we conclude that an important factor in rehabilitation is to create personalised interfaces, experiences and therapies. Each patient's needs are different, and the therapeutic approach ideally covers the physical and the mental, matching their idiosyncratic characteristics which also change over time. We found that it is difficult to sufficiently customise the standard game controllers and other interfaces. Focusing on the physical interface, we have identified a number of parameters to be varied in the individualised solutions. These are weight, size (or form factor in general), reach (in a line, a plane or 3D space), orientation, compliance (or springiness - the response of a material), friction (related to texture) and force (lateral or torque, depending on the task). While in traditional rehabilitation techniques these parameters are fixed in any situation, the aim of our research is to have as many of these parameters under real-time control. This is possible using elaborate feedback mechanisms and actuator technologies for active haptic feedback, as explored in earlier projects (Bongers, 2004a). Similar to traditional rehabilitation therapies, the aim is to develop extensive individual responses to the patient's particular needs.

In our current and near future projects we approach the customisability of the modules firstly by working in a modular way (such as the sensor tiles), further exploring the possibilities of mechanical adjustments, and utilise the flexibility offered by software and hardware. To extend the range of possible individualisation, we have explored the use of 3D printing and other CAM (Computer Aided Manufacturing) techniques which will be presented below.

Independence

It is often noticed that patients perform well when under full guidance in the rehabilitation ward, which is difficult to sustain outside the ward and even more difficult after discharge from the rehabilitation centre. This breach can be restored with novel ways of interaction between therapist and patient (and other carers / stakeholders). Many opportunities exist to address this by developing remote therapies, addressing the dichotomy of the current situation (intense therapy in the ward, left to one's own situation when discharged), and extending to a continuous therapy space covered by an ongoing but intermittent involvement of the therapist or other health professionals. It also means that the parts of the system have to be cheap, portable, and possibly based on technologies already present in the home (PC's, TV screens, loudspeakers) rather than relying on specialised and cumbersome set ups (projectors, screen mounting, overhead camera fixing for tracking purposes). Sophisticated analyses of an individual's movements will be possible and remotely located rehabilitation clinicians will be able simultaneously to provide meaningful and engaging feedback to their patients. This is particularly important for people living in regional, rural and remote areas where access to therapy is often restricted or non-existent.

Design responses to the Key Issues

In response to the three main issues as identified and presented in the previous section, this section discusses possibilities we have explored to improve interactive rehabilitation. They are based on enabling technologies, and tangible interaction design approaches (Ishii and Ulmer, 1997) (Shaer and Hornecker, 2010).

Our design approach aims to blend in, is inspired by, and follows on from existing rehabilitation therapy techniques. We are using gentle, appropriate yet radical interventions, extending from established practices with a design approach that develops through proposing and testing.

Video Games and Multimodal Feedback

Patients can be *motivated* to carry out their rehabilitation exercises using enhanced and informative feedback. We used video games with alterations, and newly developed multimodal interaction styles.

Much of the recent work in home-based rehabilitation has been driven by the adoption of Wii-style videogames by rehabilitation therapists. For example, Gil-Gomez et al (2011) have recently shown that a modified balance training system based on the Nintendo Wii Balance Board improved standing balance in a sample of 17 patients with acquired brain injury. Furthermore McNulty and colleagues have shown that an intensive two-week intervention using off-the-shelf Nintendo Wii videogames resulted in significant and clinically relevant improvements in functional upper limb motor ability in people recovering from stroke (Mouawad, 2011). However off-the-shelf products like the Wii are not suitable for a wide range of patients.

The first phase of the project looked into using video games as a way of motivating patients, however it was found that with this approach it was difficult to obtain sufficient levels of customisation. We made several successful adaptations of Wii controllers, such as extending a Wii-mote with an external switch for a wheelchair user to operate with their elbow, and an extended platform for a Wii balance board to support wheelchair use. We found that these adaptations were still quite limited due to the fixed mapping between controller movements and game parameters, and we needed more freedom to design appropriate tangible interfaces. Others have designed new games for rehabilitation purposes, from quite straightforward feedback (Jacobs et al, 2013), colourful patterns (Duckworth and Wilson, 2010), to programming 3D environments (Geurts etc al, 2011), however we focused on multimodal feedback to enhance the therapies which enabled us to find the optimal mappings between the patient's actions and the system's responses.

See also the work by Korean researchers elswehere in this book (Seo & Ryu, 2014), who particularly look at how the gamefication can be used to support the transition from the hospital to the home.

Individual Products

In addition to the ability *customise* through the creation of individual interfaces through software, recent developments in 3D printing have made it much easier also to individualise the shape of a product. The recent trend in the field of industrial design is known as 'mass customisation' (Heskett, 2002), as a response to the 20th century mass-production. Individualisation through customisation was identified as a key need in medical rehabilitation processes, as discussed above.

The notion of individual products is a significant shift in the field of industrial design, a shift towards the rather unexplored territory between *craft* (highly skilled individual labour, production of single pieces) and *industrial production* (mass made by machines). Since the transition from craft to industrialisation as the main means of manufacturing during the industrial revolution, and the reorientation (as one could call it) of the role of craft through the Arts & Craft movement, Bauhaus and subsequent developments, each found its own part of the field of production. In the last decades there have been significant developments in CAD / CAM (Computer Aided Design and Manufacturing) which are now becoming mainstream and increasingly available to smaller studios and even individuals (Hague et al, 2003). This has led to many new practices, techniques and approaches, and the opportunity to design individualised physical interfaces.

The possibilities of design (CAD) were always ahead of what was possible in manufacturing (CAM). The field of architectural design seemed to have been much further in developing parametric modelling, and "file-to-factory" approaches enabled architectural designs to rely on individually specified components rather than being limited to the use of standardised elements. This has led to the notion of non-standard architecture (Oosterhuis 2002, 2003, 2011). Product Design is now increasingly engaging with the possibilities.

Indicative of the limited notion of its potential CAM is often called rapid prototyping, which implies the (although useful) practice of using CAM to try out forms for user testing, and improving manufacturing, it is seen as a stage in the development towards mass production. There are many possibilities to explore when using CAM to create the final product. What we have been exploring in our projects is the possibility of creating *individual products* and particularly *interfaces*. We have known for a long time that, because each person is different, customisability is a crucial factor in each user interface. Until recently this was mainly applied on the software side of the computer, and to some extent through its sensors (input) and displays (output) – ideally through a mix of multiple modalities and modes (the iPhone is a good example). However the *shape*, and its physical appearance in general, is very fixed. This is in fact extremely limited, the iPhone can have text engraved, and until recently only came in the colours white and black (as in the original T-Ford marketing, ironically).

This approach of *mass-customisation* resonates well with our desire to make individual products to suit the needs of individual patients and practices. It could be described as meta-craft. It is very different from mass production, and it influences the whole design process. It offers new possibilities for including the user, client, or patient in the design process, delivering not a final product with fixed parameters but an open design with specified ranges of parameters to be determined by the user. This leads to the design approach that such a meta-craft designer needs in order to develop these 'product envelopes'. Moving away from traditional industrial design, there is a need for a different design approach when dealing with individual products and manufacturing than when designing for mass production. It influences all stages of a design process, not just the final ones. When designing for individual products, we design not just one product (or not even multiple products) but a *range* of products, through an envelope set by the encompassed parameters and their ranges. Part of our research aims to establish the heuristics, approaches and guidelines that drive and guide these design processes.

Networking and logging

To support the need for *independence*, networks can be used for tele-rehabilitation in a pervasive computing environment. This would allow a therapist to oversee the development of remote patients, and guide their exercises. In the most recent phase of our project we implemented a logging system in our devices, in response to strong requests from the practitioners, to be able to directly track and store the patient's movement and other data which is now collected on paper and often doesn't get used. This was relatively easy as the data was already in the computer, as read from the sensors in the various products, and we extended our software to write this data to a file in real time. The file is in a spreadsheet format, so that the practitioner can import the data into their patient file (which for obvious ethical reasons we cannot access directly).

Interactive Infrastructure

Inspired by the rehabilitation practices and further informed by our earlier work, it became clear that a modular approach was very suitable. The modular approach was developed in other projects in audiovisual instruments (Bongers, 2002) and architectural design and the development of the idea of an Interactive Infrastructure (Bongers and Van der Veer, 2007).

The development of interactive infrastructures has become a common approach in HCI (Human-Computer Interaction) in the last decade. The approach can be seen in the fields of Ubiquitous Computing (or Ubicomp), Pervasive Computing (as IBM calls it), the Internet of Things (MIT's Neil Gershenfeld (1999, 2004)), Sentient Computing (AT&T's term) or Ambient Intelligence (an approach supported by Philips) (Aarts and Marzano, 2003). It is a kind of electronic ecology or *e*-cology, inspired by the importance of natural ecosystems to emphasise interaction as the central area of design efforts (Bongers, 2004c). The greatest possibilities of the *e*-cology or Ubicomp lie in the potential for de-centralised systems, such as the Internet. At the scale of products, MIT's proposal for the Internet of Things is the most relevant for our project. The idea is that all modules in the system can talk to each other, for instance, when carrying out a stepping task the number of repetitions can appear on the computer screen but also on the handheld digital counter module.

The development of an interactive infrastructure fits well with the notion of embedded interaction and pervasive computing. Modules can be input (through sensors that pick up the patients actions), output (displaying feedback to the patient visually, auditory, tactually), or both. Furthermore, there are active objects which are used to indicate modes and preferences. Modules we have developed so far are an interactive hand counter (Bongers et al, 2013), a number of wearable modules for intimate tracking of arm and finger movements (bend, pressure, orientation) (Pickrell and Bongers, 2010), and a wireless handheld reaching task module (with an RFID reader, and motion sensor and visual feedback, using

RFID tagged targets) (Bongers and Smith, 2010). All these modules are interacting in real time. We are including off the shelf products in this infrastructure, such as Bluetooth speakers, tablets, keyboards, motion sensors, iPads and iPods (which we have used as wireless displays for instance)

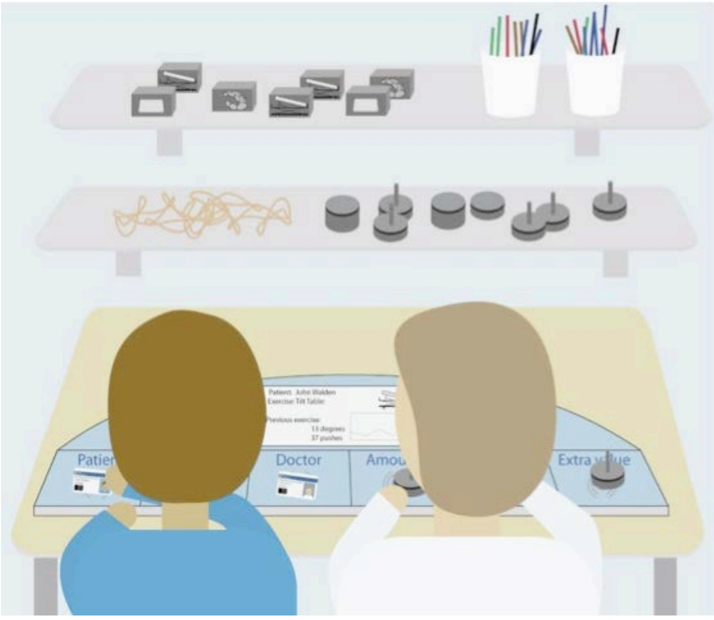

Figure 2. Tangible programming table: impression of the usage scenario

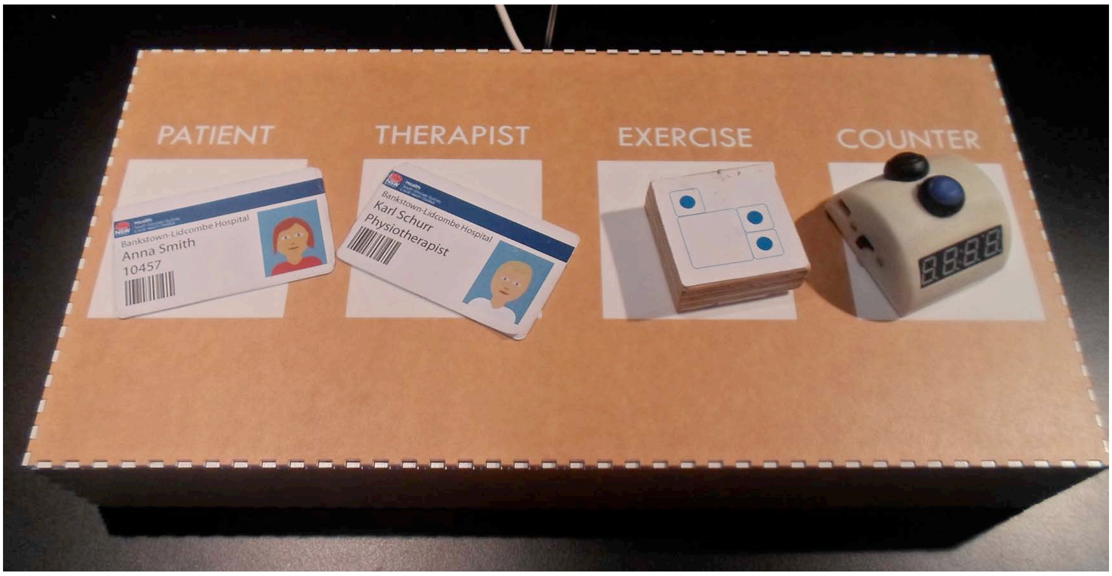

Figure 3. Tangible programming table prototype

The mapping between modules and the settings are established through placing the modules and other objects involved (representing the patient for instance) on a programming table as depicted in Figure 2, using RFID tags and multiple RFID readers (we are using a sequential polling technique we've developed to avoid interference between readers and between tags). We are also developing 'programming modules', physical objects which are part of the modular system, and which enable the therapist (or care giver) to set the parameters and variables of the task through manipulating physical objects rather than screen based programming interfaces. This idea has been presented in a working prototype (shown in Figure 3) to the practitioners on several occasions, from whom we have received positive feedback. The importance of supporting the therapists and practitioners to be able to control the parameters of the exercises has been identified by others as well (Hochstenbach-Waelen, 2012).

Interactivated Reaching Task

One of the tasks frequently employed in rehabilitation is for the patient to practice picking up an object from a table surface, then to reach to a distant point to deposit the object.
The purpose of this task is that the patient can improve their ability to interact with everyday objects in the home. An initial experiment was put together to carry out such a reaching task with enhanced multimodal feedback. Here we used an object for the user to hold and move around with an RFID tag enclosed and readers on the table, as shown in Figure 4. The task can be modified in range, and the trajectory and completion of the task is fed back with sonic and haptic signals. The trajectory can be further guided by an accelerometer attached to the upper arm, providing a means of further sonic articulatory feedback. The sonic feedback is generated in real-time using an FM-synthesis patch in Max/MSP.

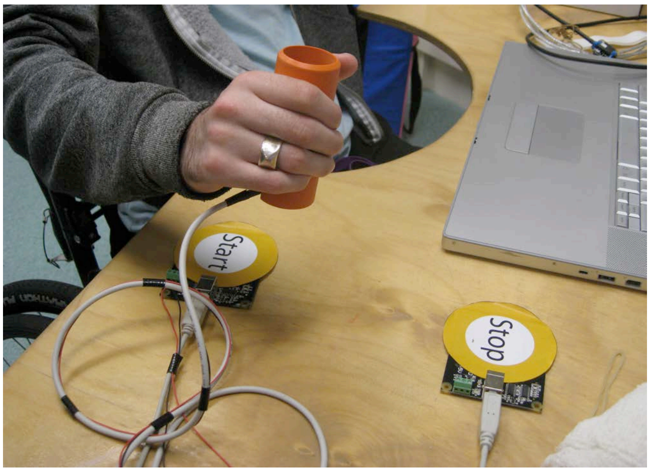

Figure 4. Reaching task tracked with RFID & motion sensor.

Reaching task device design

In 2010 a group of industrial design students and two research assistants developed a functional prototype. In this demonstrator, the reaching task targets are passive RFID tags which are colour coded, and the patient holds an interactive device which has an LED displaying the colour of the target to reach, which then reads the tag and motion data and wirelessly communicates with a host computer. The primary task is to follow a pattern of coloured lights by matching (reaching) the colour coded targets, further rewarded with musical feedback. The device contains an RFID reader, microcontroller, wireless transceiver, motion sensor for tracking 2 rotational DoF (degrees of freedom), rechargeable battery and multicolour LED as can be seen in Figure 5.

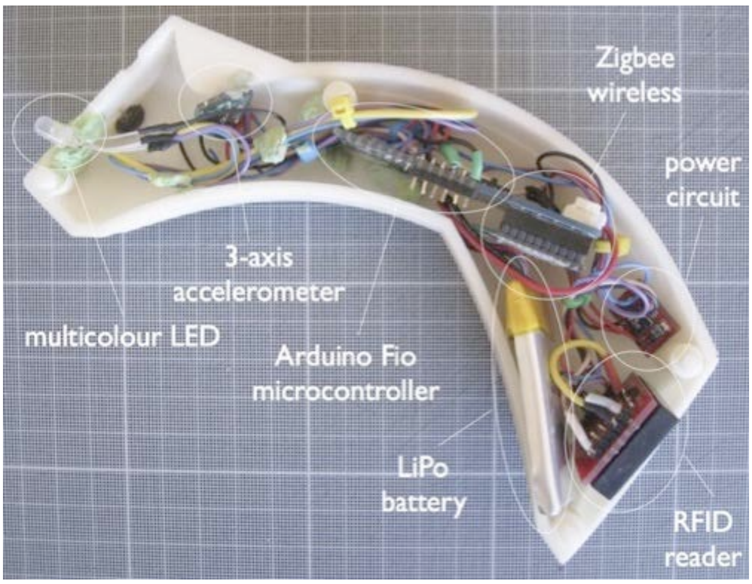

Figure 5. The wireless reaching task device inside.

The therapist can set the task by placing the tags in 3D space, and thus set the goals to be reached for a particular part of the session. The main task for the patient is to follow the colour coded targets (red, blue, green and yellow tiles) prompted by the colour of the LED on the device. The tiles are made of foamcore, a lightweight yet rigid material that supports the coloured paper. Further refinement of the therapy is possible through the motion sensor, for instance if the patient tilts the device in the wrong angle at any time, the guiding feedback can indicate this. Although the set-up is computer based, the computer screen is not the main focus of attention. The primary feedback is programmed in the microcontroller of the device, following the lights, and the music which is generated from the computer. The shape and weight of the basic device is kept to a minimum, leaving an appropriate range of customisation of physical parameters such as weight and shape by extending the device with passive elements. The basic shape is 3D printed, resulting in a rigid and light device. By adding material to the basic shape, different forms and weights can be made for individual patients.

Reaching task device evaluation

We took the device to the rehabilitation ward and tried it with one of the patients as shown in Figure 6. The device and the ideas behind it were positively received, and some problems and suggestions for improvement were made by the patients and staff. It was quickly found that due to the low weight of the coloured target objects (with the RFID tags), they tended to slide away. Sticking them to the table resolved the issue, however it decreases the flexibility. The patient also had troubles with the difference in height, as he tended to slide the device towards the objects. For a case like this it would be better to have the targets flush with the work surface, by making them thinner (which is possible) or by raising the work surface around them. These findings were interesting as the device had been tested on numerous occasions with visitors to the Interactivation Studio at UTS, many students, and a class of primary school children (3rd grade), and they never had these problems. It proved again how important it is to test with the actual target audience. One patient in particular tried really hard to convey his feedback, and was highly critical and gave very useful feedback. Further requirements followed from our discussions with therapists and patients, as well as our own observations are: robustness, easy to set up and modify, avoiding wires, no dependence on mains supply during trials (few wall outlets in hospital wards and poorly placed), and no dependence on the local network.

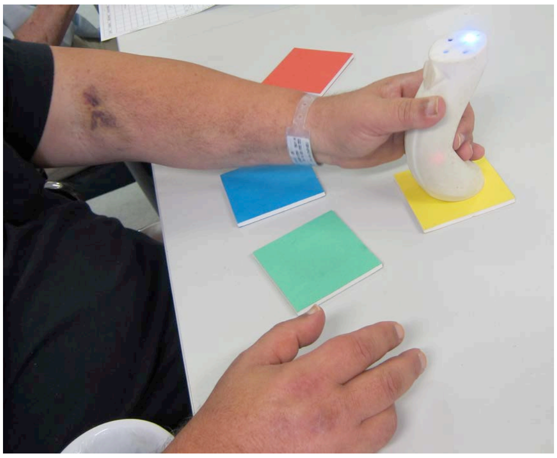

Figure 6. Testing of the reaching task device

Re-Ability Sleeve: a modular and wearable interface

Figure 7 shows an example of the outcome of an analysis of a typical rehabilitation practice, where the therapist used low cost materials to create a compound of movement and orientation requirements for the patient. While the basic task for the patient is to move from one position on the table to another one, the practitioner has set further refinements of the task: the straw guides the patient to keep the wrist at a certain angle, the styrofoam cup puts the hand in a certain posture (and has to keep it in that posture without squashing the cup), the paddle pop stick guides the thumb in the right position, etc. We took this as input for a potential design of an interactivated system, where we would use specific sensors such as a gyroscope, accelerometer, pressure sensor, bend sensor, and proximity sensor.

A fourth year industrial design student Michelle Pickrell dedicated her major project in 2011 to this subject, after having worked with us on earlier projects. She made several visits to the ward, first for observations and later to bring prototypes and systems to the practice. The prototype developed was based on a number of iterations, and is shown in Figure 8.

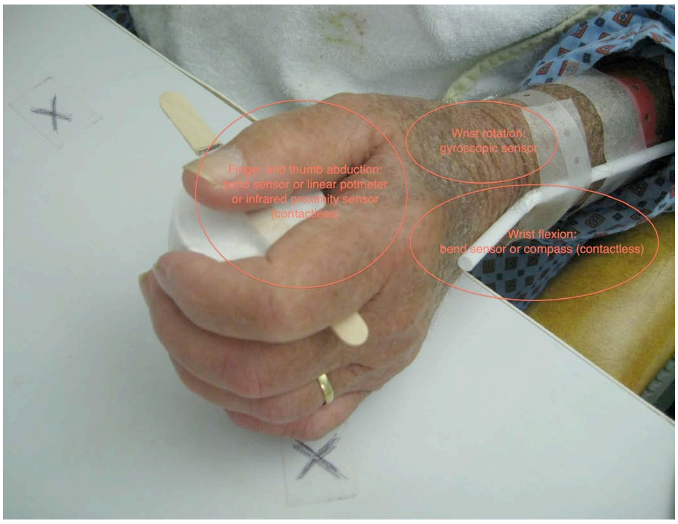

Figure 7. Translation of a mechanically supported rehab task to potential sensor applications.

Figure 8. The Re-Ability Sleeve.

Re-ability sleeve design

The system designed reflects the key issues identified in our earlier research of *motivation*, *customisability*, and *independence*. In early stages a number of interviews and brainstorming sessions were conducted with both patients, their carers and the physiotherapists at the rehabilitation clinics. At a later point of development, the design was tested by patients, modified and tested again. The final design consists of a (custom designed) sleeve, with pockets which hold the sensor modules in place. The main module sits on the upper arm, and contains a microcontroller board (Arduino Fio) and the digital radio (Zigbee), and a detachable battery pack (connected through magnetic contacts) as shown in Figure 9.

Figure 9. The battery, charger, and receiver modules.

The individual sensor modules fit in pockets in the appropriate places, and are plugged in to the main module. The current version consists of sensor modules for bending (flex sensor on the elbow, and a two way flex sensor on the wrist), a 2-axis accelerometer on the upper arm, a distance sensor (measuring the gap between the upper arm and the body), and a pressure (force) sensor on the thumb. The appropriate form of the modules was found through a number of prototypes. By making a first 3D printed prototype we were able to recognise some structural problems or weaknesses, and ergonomic considerations leading to the curved shapes with rounded edges.

Re-ability sleeve evaluation

Figure 10 shows a therapist working with a patient on a squeezing task (between thumb and index finger) sensed by a force sensor (FSR) and further guided by feedback from the accelerometer which tracks the (unwanted) movement of the upper arm.

Figure 10. A therapist working with a patient with the sleeve.

Feedback is given from a computer programmed in Max[1], using visual and auditory modalities. Various forms of feedback were tested, including videos that played according to the patient's performance. The videos would progress in response to successful moves by the patient. However we found that a simple counter or a scale display was already satisfying and therefore engaging for the patient. This principle was reinforced on several occasions by therapists and patients, confirming our approach to offer feedback in multiple modes and modalities, from which the patient and therapist can choose. This phase of the project resulted in many insights in interactivated rehabilitation practices, and was presented in demos and workshops at HCI conferences from which we received valuable feedback (Pickrell and Bongers, 2011). It was clear that the modular approach was very suitable to meet the variable demands of the rehabilitation practices, which we worked out as a key issue in our current work presented in the next section.

Interactivated Hand Counter

After having observed that a mechanical hand counter was an omnipresent tool in the rehab ward, we decided to redesign this as an interactive electronic counter. This work was carried out by student intern Victor Donker. Again we followed an iterative and inclusive design process, starting with a range of ten foam models as form studies, then offering a selection of eight different switches (mounted on blocks of foam) to choose from, and discussing the needs and design requirements with staff and patients in the ward. As always, one important requirement of the module was the connectivity, enabling the results of a rehab exercise to be uploaded directly to a computer file. We are

[1] Max/MSP/Jitter is an object based visual programming language for multimedia applications. In addition to the data manipulation part, it has a range of sound processing objects (MSP) and video processing capabilities (Jitter). See www.cyling74.com.

using an Arduino-based 4-digit 7-segment LED display from Sparkfun, connected to a Zigbee radio, and powered by a rechargeable LiPo battery (using induction charging). The version in Figure 11 shows the stage in the development where we had taken into account the stand-alone shape, which we further refined in a more ergonomic shape which is easier to hold and can be placed on a surface.

Figure 11. A hand counter module in use in the rehab ward

Modular Interactive Stepping Tiles

In response to the needs of the therapies we developed balancing and stepping task tiles. The current version is shown in Figure 1. The first version was developed in 2012 with an industrial design major project student Rebecca Hall, which resulted in a prototype that was tested in the rehabilitation ward of a public hospital in Sydney, as shown in Figure 12. This work was inspired by the exercise mat developed by Stuart Smith and colleagues at Neuroscience Research Australia (Smith et al, 2011) (Schoene et al, 2011, 2013), a design adapted from the DDR (Dance Dance Revolution) game paradigm. With this sensor mat (shown in the background of Figure 12), elderly or less mobile people can practice balancing and stepping tasks in their own home.

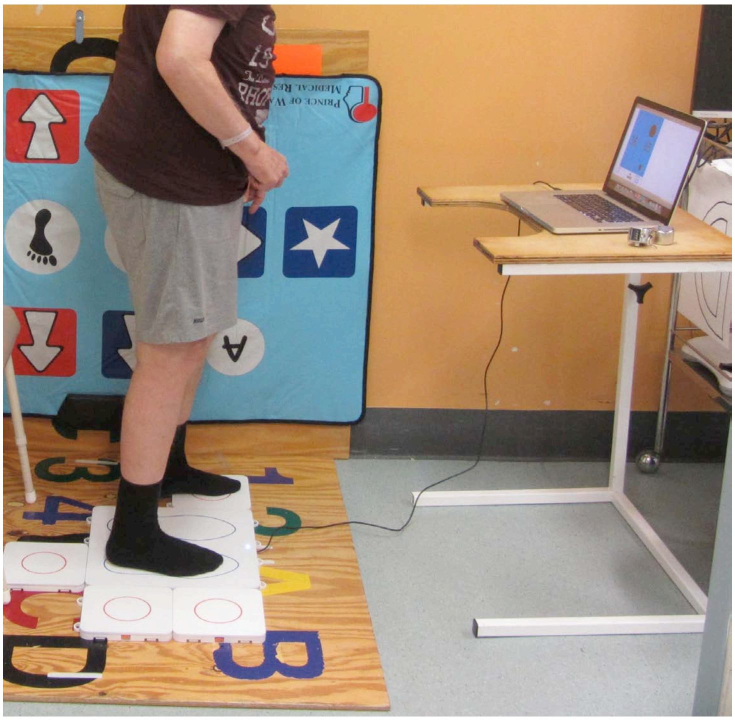

Figure 12. The first prototype in use in the ward.

The modular sensor floor consists of a main tile of 40x40cm, on which the user can place both their feet, measuring the pressure at four points under the feet, for balancing exercises. Smaller tiles (20x20cm) can be attached to the main tile on all four sides, so that stepping tasks can be carried out. The tiles are fabricated using CAM techniques. They are 20mm high making them easy to step on, which is an important design requirement for the ease of use of the tiles. Other products such as the entertainment robotics tiles (Lund, 2009) are thicker and the Wii balance board is over 50mm high. Our

design process was very much driven by the medical practitioners, who also suggested not to have visual feedback in the tiles as the patients need to not look at their feet during exercises. They asked for a surface with pressure points rather than a balance surface (such as the Wii).
Between the layers of the structure an FSR (Force Sensing Resistor) is placed under a layer of foam (3mm EVA closed cell foam) to disperse the force of the feet. This sensing technique was initially developed by the first author in an architectural project of an interactive building The Water Pavilion in the Netherlands in 1997 (Bongers, 2004b). This construction gives a continuous electrical signal proportional to the weight applied, converted by a microcontroller circuit into digital signals. The signals travel between the tiles using slightly modified littleBit[2] magnetic and spring loaded contacts (Bdeir and Ullrich, 2011).The tiles are connected via USB to a computer, which then provides visual feedback. The tiles are covered in a thin layer of neoprene rubber at the bottom to prevent sliding.

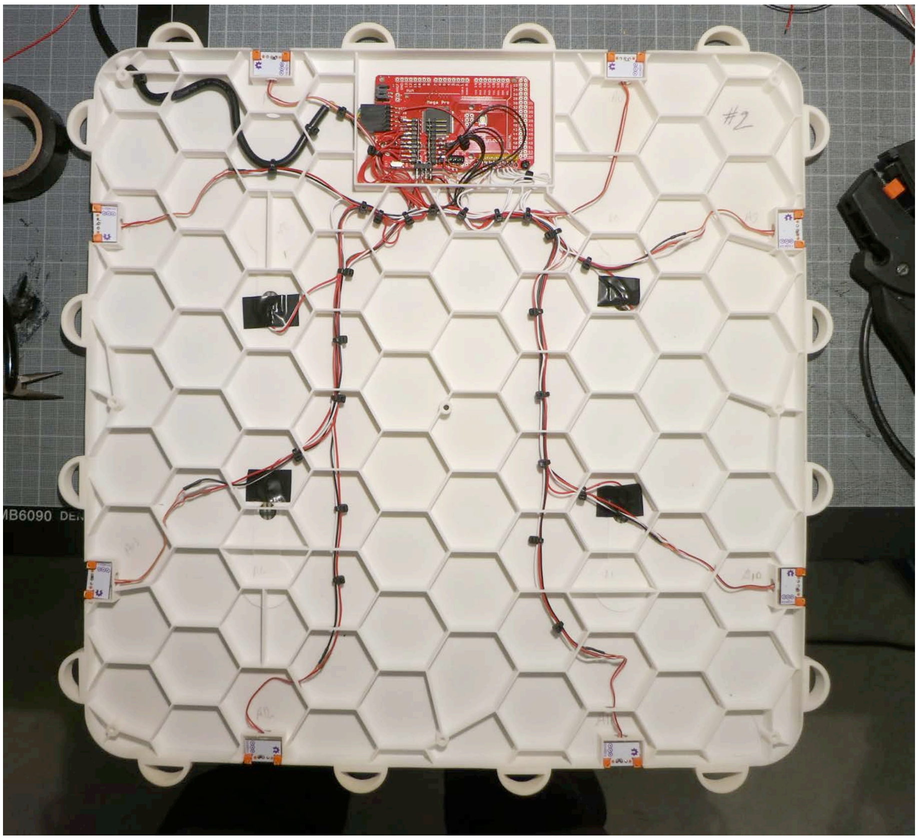

Figure 13. The 3D printed structure of the main tile with the sensor interface.

Early in 2013 a medical research group who are studying balancing exercises and falls prevention (Sherrington et al, 2008) in Sydney commissioned the development of two more sets of the tiles, enabling us to further develop the design. Improvements were made to the electrical connections and the mechanical linking of the tiles, and we made all the tiles pressure sensitive (some were switches in the earlier model). The main improvement however was to address the reproducibility by applying 3D printing techniques (the first version was made using a computer controlled milling machine, which is cheap but not suitable for larger numbers). The structure is shown in Figure 13, and was designed in Solidworks by Rebecca Hall as research assistant.
A 'bridging' tile was developed, not containing any sensors but acting as a bridge to extend the range of the stepping task. We developed a way of sensing where the tiles are attached and what type of tile they are, (sensing or bridging) so that the on-screen layout changes dynamically in response to the actual placements of the tiles. The main tile contains a Sparkfun Arduino MegaPro which links to the host computer via USB, and is shown in Figure 13.

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2 Littlebits are sensor and actuator modules that snap together with magnetic connections. The user can make various 'circuits' with these building blocks, a bit like Lego. See www.littlebits.cc

Graphical interface

A graphical interface for visual feedback, information presentation and control was developed by Victor Donker, a student intern from the TU Eindhoven, the Netherlands. The interface, shown in Figure 14, was created in Max/MSP/Jitter which was already being used to read and process the signals from the tiles. This system allows the therapist to control a number of parameters and settings to configure different types of exercises, using a touch screen or a mouse. The screen shows which tiles are connected, and displays their pressure values represented by changing the size of a circle. For the main tile the pressure can also be displayed in percentages (for balancing exercises). The subtiles show a numerical value representing the number of steps taken by the patient. On the right hand side the overall stepping count is displayed, as well as the goal to be reached. The patient's and therapist's ID are put in a field, for logging purposes. A stopwatch section of the screen allows the therapist to time activities. The left hand side of the screen is for setting the task parameters, such as number of steps and thresholds.

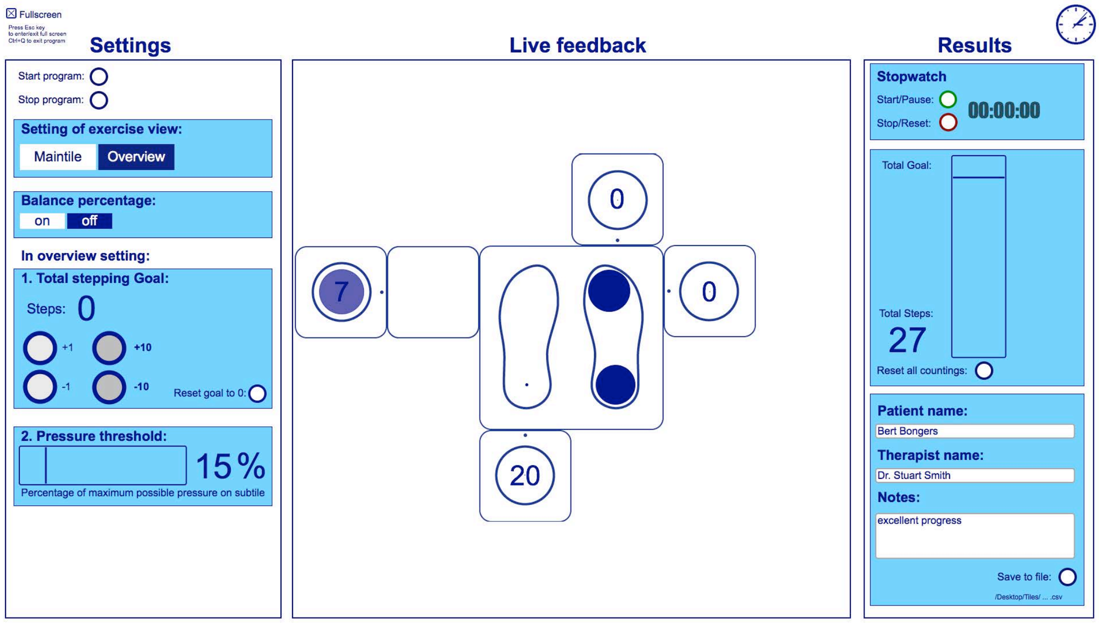

Fig 14. A screen shot of the visual interface and feedback

The modular sensor floor system is currently in frequent use in a Sydney hospital, and in the Adelaide repatriation hospital where a comparative test is being carried out (across various similar systems). Preliminary results and experiences are presented in below.

Design Process

One of the key elements of our ideas for a range of products is the customisability through individual manufacturing (this is increasingly possible using 3D printing on demand schemes). While 3D printing is relatively expensive, we needed to use this technique in order to explore the flexibility and freedom of form, so that we could create customised products for the patients. There is a strong trend of 3D printing gradually becoming more affordable. The costs of such manufacturing are largely dependent on the amount of material used, so we designed the 3D printed part to be as light as possible yet strong enough to bear the load of a person standing on it. This was achieved by designing a honeycomb structure, with 1mm wall thickness. The material used to print is ABS or polyamide, and depending on the quality of the printing machine the density of the material can be over 90%. Torsional stiffness is obtained by layers of acrylic, which are laser cut. The amount of this acrylic material is not an issue in this process, as it is cheap and the price of the process depends mainly on the length and complexity of the path that is cut. All this was done using the machines of the design faculty at UTS, with the final 3D print structures provided by the higher quality machines of the Shapeways Company (the major printing on demand supplier of 3D prints).

The tiles were developed iteratively, we made four different versions of the structure before we had the right balance between weight and strength. A finite elements analysis was performed on the computer model which confirmed the strength of the design. The torsional stiffness was important as it influenced the working of the sensor, finding the right balance. Every new version or part of the system was taken to the hospital for feedback and adjustments were made if necessary. The design took into account the situations of and knowledge from a wide range of stakeholders, such as therapists, patients, carers, medical researchers, people responsible for technical support and IT support, physiotherapists, and occupational therapists.

Preliminary Results

After several preliminary tests with the first set of the current version of the modular sensor floor system in the Sydney hospital (see Figure 15), two further versions have been in use in the hospitals in Adelaide and Sydney since April and May 2013 respectively. In this section we present some of the findings as reported by the practitioners. Some of this data is acquired using our automatic data logging system.

Figure 15. The interactive rehabilitation main tile in use.

<u>Sydney hospital</u>

One of the physiotherapists, Daniel Treacy, has been working with a set of tiles at the Sydney hospital for five months, using the system for exercising with patients for two hours every day.

He has reported three experiences of patients who all benefitted from the enhanced feedback of the interactive system in balancing and stepping exercises.

The first patient was a 60 year old, admitted for rehabilitation following a left above knee amputation. After two weeks of slow progress and low motivation he started working with the tiles. His repetition of practice figures more than doubled in the following week, and after that week he was able to move independently with the aid of a rollator frame, whereas previously he needed the assistance of two people. The patient reported to have great benefit of the feedback, where previously he felt unclear about the purpose and progress with regards to the exercises.

The second reported patient experience was that of an 87 year old male with a background of left below knee amputation (similar to the person in Figure 15), who had developed bad knee flexion contracture, and needed to do exercises to extend his hip in standing and walking. The sensor tile with the feedback was applied as a rehabilitation aid, after the patient's 5th day of therapy his results changed from a success rate in exercise task completing from below 10% to a range between 60% – 86% in the following four days.

Figure 16. The interactive floor tiles in use in Adelaide.

The third patient experience reported by the physiotherapist involved an 86 year old female who was transferred to rehabilitation after a fractured right hip due to a fall. She previously had a left sided stroke with right-sided weakness. Before the fall and fracture she was able to mobilise independently with no aids. The sit to stand (STS) exercise she was prescribed to do had the aim of getting her to balance evenly between the two feet which was difficult due to the previous stroke and pain, improved from day 18 when the tiles were introduced. While the number of repetitions performed remained constant, she was able to receive more feedback on how effective each one of the repetitions was and resulted in an improved outcome measure in terms of how much weight she was putting through both legs while standing up (The aim is to have 50% of weight through both limbs). Prior to using the stepping tiles the patient was only putting 20% of her weight through the effected leg, while after implementing the stepping tiles she was able to more than double this amount to over 40%. The patient reported that only with this feedback she realised what her balance was, which helped her to reach the more positive results.

These results are informal, but it does reveal the possible application of the system in a clinical setting.

<u>Adelaide hospital</u>

We are currently working with clinical researcher Dr. Maayken van den Berg who is undertaking a pilot study comparing several rehab exercise setups. The tiles are being used as part of the intervention program in an ongoing research study "*The effect of immediate feedback through video and computer-based interactive exercises on mobility outcome in geriatric and neurological rehabilitation*[3]" at the hospital in Adelaide. This is a space for comparative studies and therapies using several different interactive systems, such as Nintendo Wii based and Microsoft Kinect based systems, dedicated systems, and the interactive floor tiles as shown in Figure 16. Of those patients that have used the tiles (6 out of 7) the average time they were active (not resting or moving in between exercise stations) during the therapy session was 30min (based on 28 intervention sessions, intervention period still ongoing), of which on average 9 minutes were spent doing exercises on the tiles.

The system is now being tested with 40 patient volunteers. In 2014 the floor system will be part of a larger study "*Affordable technology to improve physical activity levels and mobility outcomes in*

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[3] More information about the trial can be found at the Australian and New Zealand Clinical Trials Registry: https://www.anzctr.org.au/Trial/Registration/TrialReview.aspx?ACTRN=12613000610730

rehabilitation", an NHMRC[4] Project Grant awarded in November 2013 to A/Prof Cathie Sherrington form The George Institute, partnering with several universities in Australia (the first and second authors are investigators). The project will conduct a pragmatic randomised trial with 300 participants which primarily aims to establish the impact of tailored use of affordable physical activity technologies in addition to usual care on physical activity and mobility at 6 months after randomisation.

Future Outlook

The sensor tiles have been in continuous use in both hospitals, and a third set is in our lab for development and demonstration purposes. The material costs of each set (consisting of 1 main tile, 4 subtiles, and two bridging tiles) is about $1100, plus assembly costs. This puts the system competitively between the low end mass fabricated game controllers applied for this application domain (a couple of hundred dollars) and the purpose developed solutions which commonly cost $10-20k. Several other hospitals have asked to buy a set.

The aim has been to design the tiles in such a way that they can be assembled with minimal manual labour. The current version still requires quite a bit of skilled work to assemble, soldering all the connections, and some mechanical bits. The easiest way to resolve this is to make the tiles entirely stand-alone, and have them connect wirelessly to each other and/or the computer. Wireless technology however also requires a battery (the current version is powered from the host computer via the USB connection), and a charging system. We have developed all this in one system, assembled from off-the-shelf components, including induction charging which means the tiles can be charged without wires. It is then possible to seal the tiles, for easier cleaning. The increase in costs of the parts is justified by the potential decrease in costs of assembly, with the added benefit of a wider range of possible configurations of the tiles. Currently this is limited to eight sub-tiles, which is enough for a wide range of therapies and exercises but further possibilities include creating a path to walk along to perform gait analysis, which is often required in the wards.

It was interesting and rewarding to see that the tiles are used so intensively, and for many unforeseen purposes such as a sensor surface for pushing against for patients who exercise on a tilting bed, patients with prostheses, exercises which involved balancing on a thick piece of foam on top of the tiles, and stepping up. Some of these applications call for further extensions and modules.

Figure 17. Extended use and modifications of the interactive floor tiles.

Several further extensions of the sensor tiles are under development, mostly prompted by experiences in the rehabilitation ward. For instance, due to the modular nature of the tiles, it is possible to put a sub-tile on a raised surface to create a more difficult stepping task. For this and similar activities it is useful to have an extension lead. The edges of the surfaces are a bit sharp, so we are experimenting with ways to create ramps out of acrylic or foam or 3D printed material.

There are further developments in the software too that we have not yet tested in practice, such as a method of visually cueing the patient's desired movements through highlighting the tiles on the screen.

We have shown in this chapter that the tiles fulfil the need for increasing patient's *motivation*. Furthermore, we have a lot of anecdotal evidence that it is really successful with patients, for instance a very problematic patient did not seem to be able to move by himself (in a pushing up exercise on the

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4 NHMRC is the National Health and Medical Research Council in Australia.

tilting bed), until he received the graphical feedback of the system. Furthermore we are working on sonic feedback to further support the exercises.

The interactive infrastructure approach can leverage the possibilities of the individual modules. This infrastructure consists of a number of modules and objects, each with a specific purpose such as sensing (weight, movement etc.), displaying (presenting information to the patient and therapist / trainer), or acting as tokens. The modules can communicate with each other (mostly wirelessly), so that there is a continuous flow of movement information and relevant feedback across the modules of the system. Together with the practitioners, and based on our own observations, we have identified a number of other possible modules for performing several measuring and feedback tasks as part of the exercises. There is also an ongoing need for simple and stand-alone modules (the hand counter can operate stand-alone) for patients to use in their own environment. This can possibly be based on smart phones and tablets, as many patients have these, for which we need to develop Apps that can present the patient's exercise data and give feedback in a similar way as applied by products such as the Fitbit, Jawbone and Nike+.

Through this approach of modularity a large part of the demand for *customisability* can be addressed, and it can be further extended by fully applying the printing on demand model where the practitioners can order the right size of the tile (within limits). Although several designs were developed for graphics to put on the tiles, in the end we decided to leave them blank which allows the use of stickers and whiteboard markers by the therapists supporting a wide range of uses.

The system is very easy to set up and can potentially be used by the patient in their own room in the hospital or even at home, supporting the need for *independence*. The logging system keeps track of the patients exercise results, linked to his ID and time of exercise. This data can be shared in real time with a physiotherapist through the Internet, enabling the possibility or remote rehabilitation.

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We thank the staff of the hospitals involved for all their invaluable input and feedback on our developments. Particularly physiotherapist Karl Schurr has played a crucial role in all this work, with his deep understanding of all the issues related to patients exercises and motivation, and has driven many of the design processes presented in this chapter.

The project has ethics approval nationally, site specific, and from the university.

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