Interactivating Rehabilitation through Active Multimodal Feedback and Guidance

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ABSTRACT

This chapter outlines a Human-Computer Interaction inspired approach to rehabilitation of neurological damage (e.g. spinal cord injury) that employs novel, computer guided multimodal feedback in the form of video games or generation of musical content. We report an initial exploratory phase of a project aimed at gaining insight into the development of spinal cord injury (SCI) rehabilitation tools. This exploration included observation of a number of patient interactions in their current rehabilitation routines; the development of initial prototype proposals; and finally through to the development of rapid prototypes which can be used in rehabilitation settings. This initial phase has yielded an understanding of the issues surrounding the development of novel technologies for rehabilitation that will direct further research in the area of rehabilitation engineering Through the integration of novel methods, in particular the use of interactive physical devices, to the rehabilitation of SCI patients, larger scale research into efficacy of the devices we are developing can be undertaken. These developments may eventually beneficially impact upon the instruments used, the training methods applied and the rehabilitation routines undertaken for individuals living with neurological damage.

INTRODUCTION

The process of rehabilitation involves many repeated and precisely prescribed movements to be carried out by the impaired patient in consultation with a therapist. It is important for the therapeutic process to follow an established pattern of movements of individual limbs and body parts, and a guided development of these movements over time. The development of the rehabilitation intervention is determined by the range and type of movement dysfunction suffered by a patient and progression is only achieved after many repetitive movements.

Two problems have been identified which potentially can be solved by using techniques of multimodal interaction with computer generated guidance and feedback. The first problem is boredom or lack of motivation to continue in rehabilitation due to the repetitive nature of the tasks. We propose that the repetitive nature of rehabilitation tasks can be addressed by making the tasks more fun and engaging by providing multimodal and multi-levelled feedback. The second problem is the need for continuous monitoring and guidance of progression by the therapist, which can be addressed by programming interactive algorithms which respond to the patient's progress with appropriate feedback and guidance (again using multiple modalities).

Our approach is to draw inspiration for designing such systems by looking at existing interactive systems that incorporate such rich (multimodal) feedback and behaviours such as found in video-games, virtual reality, and electronic musical instruments. Our approach is further supported and guided by theoretical insights developed in the scientific discipline that studies Human-Computer Interaction (HCI). Both these application domains (inspiration) and theoretical frameworks (support from HCI) are further described in the next section.

There are different types of rehabilitation therapies related to different causes of injury (such as neural damage resulting from stroke, spinal cord injury after an accident, traumatic brain injury or sporting-related injury). It is not always possible for the patient to regain all movement freedom and skills (restorative approach, see below), but in any case therapy is at least important for preventing further loss, and developing coping and alternate movements (compensatory approach, see below).

The aims of this chapter are to (a) give a brief overview of procedures in rehabilitation medicine such that designers and engineers can begin to understand the nature of the problems faced by rehabilitation therapists and patients, (b) describe some of the principals of human-computer interaction design that may be appropriate for application to the domain of rehabilitation medicine and finally (c), to report an explorative project which aimed to gain further understanding of how augmented, multimodal feedback can be applied in a rehabilitation setting. The specific rehabilitation issue we explored concerned with the problem of upper body balance training in Spinal Cord Injury (SCI). The project took place between September and December 2009 and pursued three strands of investigation which worked towards development of novel technologies for training upper body and limb movements in spinal cord injury (e.g. Figure 1).

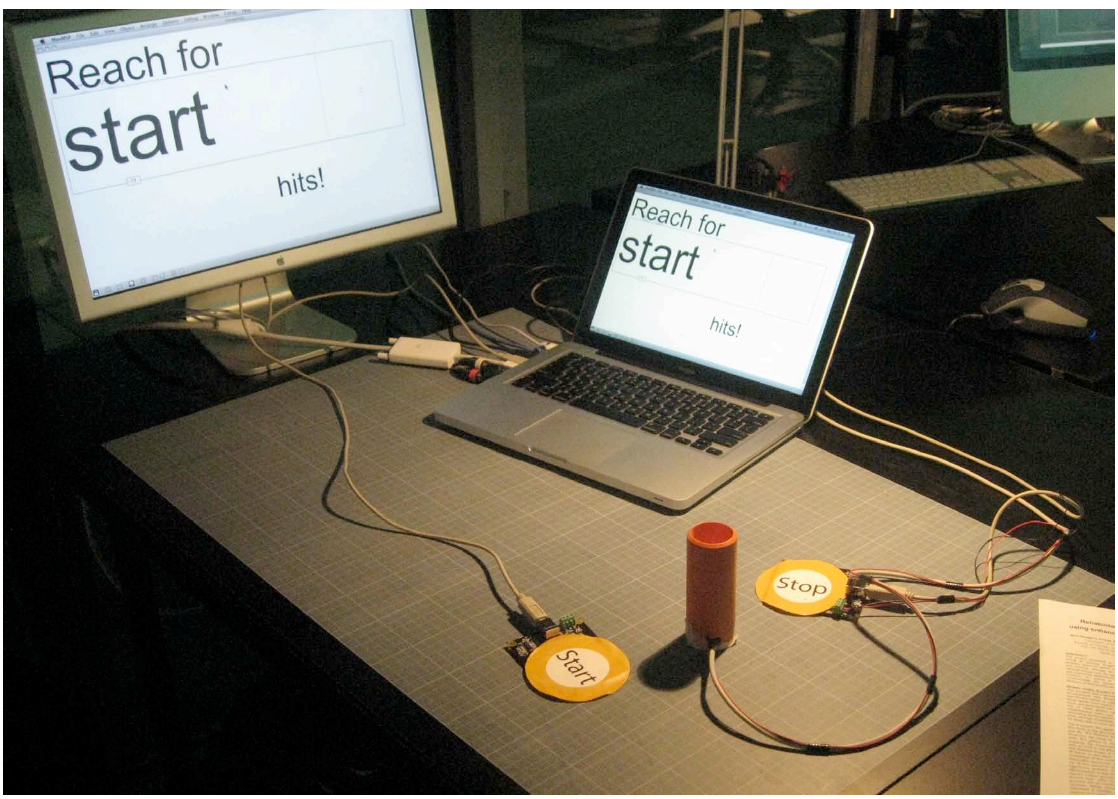


Figure 1. An interactivated reaching task for rehabilitation purposes

BACKGROUND AND INSPIRATION FOR THE WORK.

In the past two decades there has been a significant transformation in our understanding of the extent to which functional recovery is possible following damage to central and peripheral nervous systems. In parallel with advances in the neuroscience of nervous system recovery, new technologies have become more easily available and applied in fields of research in interactive systems such as in virtual reality, and computer games, electronic musical instruments, and wireless sensor networks. The aim of the section of this chapter is provide an introduction to the process of rehabilitation and how recent advances in the research field of Human-Computer Interaction, musical instrument design and video gaming technology have been leveraged to develop rehabilitation systems for application to a range of functional impairments resulting from damage to the brain and central nervous system.

Rehabilitation of brain and nervous system function

In this section we describe the medical background of the project, consisting of an overview of types of injuries, and rehabilitation practices. Thorough knowledge and insights in the nature of the therapies enables understanding of further enhancements and developments.

Stroke and spinal cord injury

Damage to the brain and central nervous system by stroke or injury is frequently associated with significant functional impairment for the individual. Stroke is one of the leading causes of death and disability throughout the world, and is the leading cause of disease burden. A recent survey of community-dwelling adults in the United States (Chan et al, 2002) found that 44% of patients who had suffered a stroke reported having limitations in most, if not all, activities of daily living (such as bathing, cooking, dressing), most of which require the coordinated efforts of posture, head and limb control strategies. Significant impairments in the activities of daily living also prevail in individuals with spinal cord injury (SCI). The physical and functional impact of spinal cord injury will vary according to both the type and level of the injury. The type of SCI is generally classified into two categories, complete and incomplete injuries. A complete injury occurs with a total severance of the spinal cord, and there is a total loss of motor and sensory function below the level of injury. Complete spinal injuries are always bilateral, i.e.: affecting both sides of the body equally, and voluntary movement and physical sensation are absent below the level of injury. An incomplete spinal cord injury occurs with a partial severance of the spinal cord, and the individual will still retain some sensation below the level of the injury. The functional effects of an incomplete injury are variable, and the individual may have more function on one side of the body than the other (Hollar 1995).

Rehabilitation of stroke and SCI

The rehabilitation of stroke and spinal cord injury patients can be best understood in terms of being an ongoing collaborative process between the individual and their care givers, which aims to restore them to their maximum potential in all areas of life (Hammell, 1995). In practice, rehabilitation interventions employ a dual strategy to achieve this aim. First, there is the *restorative approach* that aims to restore an individual's highest level of functional ability, according to their level of injury. And secondly, there is the *compensatory approach* that addresses ways of compensating for any shortcomings in function by using adaptive techniques, such as lowering the level of kitchen countertops to make wheelchair access easier, or by using equipment, such as electric wheelchairs (Trombly, 1995a). Individuals in rehabilitation are encouraged to reach the highest level of expected functionality for their level of injury by accomplishing a series of functional goals. These goals are set in conjunction with the patient's care team and aim to teach individuals new ways to manage their daily activities, and can include such tasks as eating, dressing and eating.

Success in achieving these functional goals is affected not only by an individual's physical abilities, but also by their general health, coping skills and psychological well-being. To successfully manage the various influences on therapeutic outcome, the rehabilitation of SCI in a hospital setting involves the collaboration of a number of professionals across a range of different rehabilitation services (Case-Smith, 2005). This multi-disciplinary healthcare team, in collaboration with the patient, will plan and structure a patient's goals, and regularly communicate about their progress to ensure that treatment is effective. Typically, a patient's rehabilitation experience will involve care by medical and nursing staff, who are responsible for all aspects of a patient's ongoing health issues, physiotherapists, who will help optimise a patient's physical capacity and mobility, psychologists, who will assess a patient's cognitive and sensory abilities, and assist them in adjusting to their new circumstances, and occupational therapists, who train the patient to become as independent as possible in carrying out their activities of daily living. The efforts of this healthcare team are supported by community liaison services who will help ease the patient's transition back into the community after discharge from hospital.

The role of the occupational therapist in rehabilitation

Occupational therapy is focused on helping patients to reach the highest level of physical and psychological independence that their injuries, homes and work environments will allow (Grundy & Swain, 2002). This is achieved through the use of purposeful and meaningful activities, such as stirring dough to make cookies, or picking up and sorting small coins. These exercises are designed to both assist in a patient's physical rehabilitation, and also encourage and motivate them to participate fully during therapy. They also help to improve a patient's physical coordination and dexterity, as well as increase the range of motion, strength and endurance of their limbs. Purposeful and meaningful activities also improve a patient's problem solving strategies, so that they may be able to successfully deal with the everyday challenges their condition brings (Haugen & Mathiowetz, 1995).

Occupational therapists work with a range of individuals, who, for whatever reason have difficulty in accessing or performing the activities they require to lead meaningful and satisfying lives. The role of the therapist in rehabilitation includes assessing a patient's functional ability and selecting a variety of tasks for the patient to practice in order to restore, or compensate, for loss of function in a particular area. The therapist may also act as coach during the process of rehabilitation, demonstrating how to complete a given task, and also providing feedback on a patient's performance (Higgins, 1991). Each patient will engage in an individualised program during their rehabilitation, which is designed to improve their ability to perform everyday activities, and can include retraining to eat, dress, wash, cook and even drive an adapted vehicle. Occupational therapists also provide for a vocational assessment, to prepare the client for re-entry back into the community, and review their options for returning to work. To further support a patient's move back into the community a liaison occupational therapist will also visit a patient's potential home and job site and recommend how these can be adapted for optimal use.

Engaging patients in rehabilitation therapy

In occupational therapy, rehabilitation of function is achieved through the use of purposeful and meaningful activities such as completing a jigsaw to train fine hand movements, or throwing and catching a ball to promote motor coordination. It is the meaningful and purposeful nature of these activities that are the key therapeutic qualities of an occupational therapy intervention, as it is purposefulness that organises behaviour, while it is meaningfulness that motivates performance (Trombly, 1995c). Given that a patient's daily program of rehabilitation will typically involve three or more hours of physical and occupational therapy, motivation is an important component in therapy, enabling them to engage at their maximum capacity, and derive the greatest benefit from their rehabilitation.

A patient's level of motivation is widely accepted as a key indicator of the success of inpatient rehabilitation interventions (Maclean & Pound, 2000), yet there exists an inherent difficulty in defining and measuring such an abstract component of human performance. Lenze and colleagues (2004a) suggest a more useful alternative is to measure the level of participation in therapy, as participation is an overt behaviour which can be directly observed and quantified. Examining a patient's participation level in rehabilitation has the added benefit of allowing clinicians to document not just the quantity, but more importantly, the quality of a therapeutic intervention. A further study by Lenze and colleagues (2004b) suggests that the level of a patient's functional outcome in physical therapy is directly related to their participation during rehabilitation. These researchers observed 242 hospital inpatients, with a variety of physical impairments, during their rehabilitation. They found that those who were rated with higher levels of participation in therapy showed a higher percentage of functional improvement (as indexed by the Functional Independence Measure (Keith et al, 1987)) and had a shorter length of stay in hospital than those who were rated as having lower levels of participation. Although this study did not examine participation levels for each patient category, and comparisons across impairments can be problematic, it does indicate that the level of participation has an impact of the functional benefits of regular and repeated therapy.

High levels of patient participation are also desirable during occupational therapy, especially when retraining a patient to perform activities of daily living, such as grooming, eating, bathing and dressing. The more successful a patient is at acquiring the skills to perform these activities the greater opportunities they will have to function independently when returning to the community. Having the highest possible level of independence can also help the patient to foster a wide range of social and leisure activities, enabling them to live more satisfying and meaningful lives (Hansen & Atchison, 2000). In practical terms too, the more independent a patient is the less their physical condition will be experienced as a handicap, and the more capable they will be in pursuing their own interests in terms of education, employment and family life.

According to Christiansen et al (1998) the level of participation in occupational therapy can also contribute to a patient's psychological well-being, as occupational therapy presents them with an opportunity to choose activities that express their individual identities, allowing self-actualisation and providing a platform for self-expression. This view is also supported by Rebeiro and Cook (1999) who suggest that the experience of occupational engagement can result in a positive spin-off in terms of mental health and overall well-being. These findings have particular importance for the rehabilitation of SCI patients, considering the high incidence of depression among the patient population (Elliott & Frank, 1996; Kennedy & Rogers, 2000). Depression can act as a confounding factor in therapy, and patients with depression have been found to require longer periods of rehabilitation. Higher levels of participation in rehabilitation therefore appear to be a vital element in successful therapeutic outcomes, both in terms of improving a patient's overall health, but also in the development of functional abilities and practical life-skills.

The problem of motivation

Traditionally, the purposeful activities designed to encourage participation in occupational therapy have involved the use of handicrafts such as basket weaving, wood carving, and sewing. These activities, aimed at developing sensory and motor coordination, are, by their very nature repetitive and tend to be tedious if not varied over the course of a therapeutic program (Trombly, 1995b). As a therapeutic medium these activities are functional, but present a limited appeal to a modern patient population, and it is more common today to find a computer or games console in a family home than traditional craft activities. In instances (such as spinal cord injury) where the patient population is overwhelmingly young and male (O'Connor & Murray, 2006), these craft activities may also be particularly unsuitable to fully engage them in their rehabilitation. Society has changed dramatically since the early days of occupational therapy, and so too have the interests and expectations of patients who attend for rehabilitation. These interests and expectations need to be considered if patients are to be encouraged to participate at an optimal level during their therapy.

Conventional occupational therapy interventions are also less than ideal from a clinical perspective, as they provide little opportunity for grading the level of task difficulty, and so may be too difficult for patients beginning rehabilitation, and yet fail to challenge more able patients. These activities are also limited in their capacity to encourage the development of dynamic balance, which entails maintaining balance and equilibrium while in motion, a skill that is essential in carrying out activities of daily living, from shopping to driving a car. Given the limitations of conventional occupational therapy activities and the importance of keeping patients engaged and motivated in therapy, it is an ever present challenge for therapists to find activities that are meaningful to the patient, yet still possess a therapeutic value. In the following section we explore how Human-Computer interaction (HCI) tools could potentially be used to address the issue of patient compliance and motivation, especially with regard to rehabilitation, by developing novel, engaging, interactive rehabilitation technologies.

Theoretical background and support tools from HCI

The scientific field of HCI studies, and the design field of Interaction Design, applies knowledge for creating solutions that connect people and their technological environments (Dix et al, 2004; Rogers et al, 2007). Since the 1980s, the field of HCI focussed on cognitive and conceptual layers in interaction, and has mostly concerned with creating solutions for carrying out tasks. Since the late 90s the notion that designing interactions is about creating experiences became widespread, in a way following more mature media such as theatre, film and music (McCarthy & Wright, 2004). Both in the HCI and the design communities it is now realised that physical interaction, multiple modalities, and embodiment are crucial (McCullough, 1996; Dourish, 2001).

Designing for expression is as important as ever, more complicated than ever (yet better facilitated too, due to new interface technologies, sensors and actuators, see below), and potentially more rewarding than ever before as new opportunities for ways of expression may become available. In order to facilitate expression through technological means, we need interfaces. This is particularly the case with (digital) electronic technologies, which can only be used through the interface. Interfaces allow for interaction, the two-way process of human expression and computer feedback and behaviours. By externalising our thoughts, feelings and concepts, we can articulate and refine them.

Interactivation Research

The term *interactivation* refers to the activity of making things interactive, which is a means not a goal in itself. The goal in this context is to enhance and augment rehabilitation therapy by making the objects, tools and processes interactive. This is a two-way process, by using sensors a computer can gather information about patients movements, and through the knowledge programmed into the system, as well as through further input from the therapist, the computer can respond by displaying sounds, images and movement. This computer generated feedback to the patient enhances the normally passive interaction and as a consequence, can potentially increase the engagement by the patient with his/her rehabilitation process.

The overall goal of the interactivation approach is to open up and to demystify technology, and to also make technical environments and products less challenging to use and interact with. Now that it has become easier (even trivial) to connect the real world (where we human beings and our natural environment interact) to the 'virtual world' (parameters of media and designs we work with) the design process and efforts can concentrate on the *mappings* between real and virtual worlds. Finding the optimal and effective mappings between real world parameters (potentially meaningful movements and utterances picked up by sensors) and system parameters (its behaviours, presentations, responses and feedback) is one of the goals of interaction design.

Multimodal Interaction

When interacting with the world around us, and the people, objects, spaces, equipment, natural features that populate it, we are required to successfully recruit many different sensory modalities such as vision, hearing, feeling (tactual perception which has sub-modalities of motion (kinaesthesia), force (through proprioceptors) and touch (cuteneous sensitivity) (Loomis & Leederman, 1986). There is also a rich variety of modes of communication with the world, such as through text, speech, icons and gestures that can be discerned within the interaction channels (Kress and Van Leeuwen, 2001). In the developing (time-based) interaction dialogues different types of feedback occur related to different levels of interaction. We have recently developed and published a model based on our research for the analysis of multimodal interaction and for the design of new interfaces (Bongers & Van der Veer, 2007).

The standard way of interacting with computers is traditionally very limited and mostly unimodal, however research and design from specific application areas (such as music, architecture, augmented environments) show the potential for rich and multimodal interaction. Human-Computer Interaction research in the last 20 years has increasingly put efforts towards multimodality (Schomaker et al, 1995; Oviatt, 2002).

Physical Interaction

There has been a shift in HCI towards an emphasis on physical interaction and a stronger connection with the real world, often called physical computing (Igoe & O'Sullivan, 2004). In the recent years novel, low cost hardware interfaces have appeared and become cheaply available such as the Phidgets (a spin-off from the HCI research group of Prof. Saul Greenberg at the University of Calgary), Teleo Tools by Making Things, and the Arduino hardware (in combination with the programming language Processing) (Raes & Fry 2007).

The Physical Interface Design Space (Bongers & Harris, 2002) is a tool for analysis and design of interfaces at the physical level. This design space creates a technical description, based on sensors and actuators (input and output transducers respectively), but approached from the perspective of analysis of human movements. All human movement can be broken down into a series of relational movements of limbs about joints. We can therefore describe the motion through space of any point on any limb in terms of: three lateral degrees of freedom (DoF) along dimensions of space (nominally the x, y and z axes, Figure 2) and three rotational DoF's around those same axes (the latter are also referred to in robotics terms as pitch, yaw, and roll, respectively).

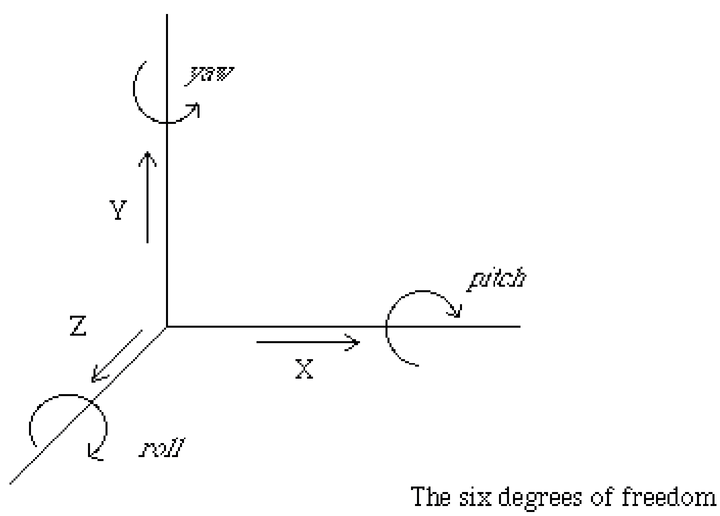


Figure 2. An overview of all six degrees of freedom of a point in 3D space.

In addition to describing the linear or rotational component of movement, each kind of movement that is engaged in an interaction with the environment can also be described in terms of the *range* and *precision of movement*, as well as in terms of the *haptic feedback* provided by the interaction.

The *range* of the movement (lateral or rotational) is an indication of whether the interaction occurs on the intimate scale (in the hand or close to the body), the bodysphere (around the body, within the reach of arms and legs), and the spatial. The lateral DoF's are measured in the SI unit of meters, meter / second in the case of speed, and meter per second-squared in the case of acceleration. Rotational DoF's are measured in radians.

The *precision* parameter involves the amount of information describing the movement, mostly related to the conversion from physical quantities into either analog or digital electrical signals (including the translation of analogue into digital). The precision is influenced mainly by the following factors: the number of bits to encode the analog signal in digital form (resolution), the sample rate of signal acquisition (or refresh rate when it concerns output), and latency and jitter (fluctuation) issues.

The *haptic feedback* parameter is concerned with 'how it feels', the forces perceived as part of the interaction due to the mass of the objects manipulated etc. This is an important parameter playing a role in the *articulation* of the movement (Hix & Hartson, 1993). When a system has active haptic feedback (such as force-feedback displays and vibrotactile actuators) the 'feel' can be interactively changing depending on the input and system behaviours - including the case of feed-forward for instance when the user is pulled towards the goal by actuators such as motors, solenoids, or shape-memory alloys (Bongers, 2002).

Musical Instruments as an example of interaction design.

Musical instruments are among the best examples of interfaces designed to enable the player a rich form of expression. The introduction of digital electronic technologies led to a disconnection of the physical sound source and control surface. This disconnection was facilitated by the MIDI protocol which became widespread since the mid 1980s. This decoupling of sound source and interface led to new instruments in the 1990s such as Don Buchla's Thunder and Michel Waisvisz' The Hands (Krefeld, 1990; Bongers, 2007), several glove-based instruments (Paradiso, 1997; Miranda & Wanderley, 2006) (Figure 3), extensions and modifications to existing instruments such as a trumpet (Impett, 1994) (Figure 4), and subsequently to a whole new field of research and development. The technologies and techniques developed and applied in this research field (Bongers, 2000) can be translated and applied in the interactivation of rehabilitation tools, as presented in this chapter. In the following section we will address how multimodal feedback technologies can be applied to the problem of spinal cord injury.

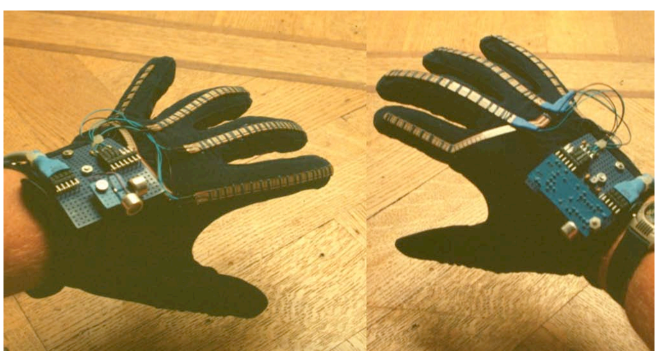


Figure 3. Instrumented gloves for musical performance.

Figure 4. An extended trumpet.

SPINAL CORD INJURY TRAINING ENHANCEMENT USING HCI

As discussed above, existing rehabilitation training tools and techniques for SCI can often be dull and repetitive for the patient, leading to poor adherence with rehabilitation intervention. One possible method by which compliance with rehabilitation programs could be improved involves the use of video games. Video games have been used across a range of health contexts from training of surgeons (Rosser & Lynch, 2007), to rehabilitation of upper limb function in stroke patients (Henderson & Korner-Bitensky, 2007; You & Jng et al., 2005), pain management in burns units (Das & Grimmer, 2005), treatment of childhood and adolescent obesity (Madsen & Yen et al., 2007) as well as delivering cancer (Beale & Kato et al., 2007) and diabetes (Lieberman, 2001) education to children. Interactive video games (Nintendo Wii, Konami Dance Dance Revolution, Sony Playstation Eyetoy), which combine player movement, engaging recreation, immediate performance feedback and social connectivity via competition, have also been shown to promote motivation for, and increase adherence to, physical exercise amongst children and young adults (Maddison & Mhurchu et al., 2007; Graves & Stratton et al., 2007; Warburton & Bredin et al., 2007; Epstein & Beecher et al., 2007; Baranowski & Buday et al., 2008). Using computers in other ways to generate guidance and feedback in rehabilitation tasks has become quite common, as can be seen in a recent application (Annett et al, 2009)

The project reported in this chapter aimed to develop interaction solutions to the SCI rehabilitation process in order to enhance the immediate feedback given to both patient and therapist and to help with longer-term evaluation of any patients progress. Video games can make the rehabilitation tasks more engaging and rewarding for the patient. Rewards come both in the short term, through immediate feedback, and in the longer term by being able to show progress (e.g via a score) over time. The Nintendo Wii game console is particularly popular in the field of rehabilitation, as the physical controllers such as the Wii Remote and the Wii Balance board support gestural movement based interaction. However, there is a limit to the number of SCI patients able to interact with these games due to the inflexibility of mapping of the functional abilities of patients onto game play, as well as restrictions imposed by the physical form factors of the controllers. One common practice is to strap the Wii Remote to the hand of the patient (Figure 5), and hope that the orientation of this controller device is sufficient to enable successful interaction with games such as tennis, bowling etc.

Figure 5. A Wii Remote strapped to the hand of the patient

If this cannot be achieved, it is ‘game over’ and patients rapidly become despondent with game play leading to a discontinuation of engagement with the technology. Our team has identified a number of problems and opportunities to explore how video game play can be used as a therapeutic rehabilitation tool and we have outlined a structured approach to designing new ways of interacting for rehabilitation purposes. The project described is part of an ongoing collaboration between the Prince of Wales Medical Research Institute and the Interactivation Studio of the UTS Faculty of Design, Architecture and Building in Sydney, Australia. The researchers and designers worked with several rehabilitation therapists to gain further insight into the practice, problems and opportunities of occupational therapy.

During this project several patients with a spinal cord injuries also joined the team as collaborators to play the games and provide feedback on the technologies we developed. The patients brought to the project experience in video game play and the ability to offer suggestions related to the movement limitations resulting from their injuries. One of the difficulties in ongoing testing has been in finding appropriate patients that are able to undergo longer-term therapy sessions, but for this exploration and experimentation phase the help of incidental users was extremely useful.

Technologies and tools

The Nintendo Wii platform has recently gained a great deal of media exposure and has become is popular in rehabilitation facilities. The advantage of the Wii system is that it is based around the physical controllers which allow a cheap way of obtaining relatively rich movement data from the players. However, the Nintendo platform is quite closed compared to other game environments, and hard to program for or 'hack into'. This limits us to modifications to the hardware, in the electronics and physical shape of the controllers, in order to change the mappings. Furthermore, many off-the-shelf games are entirely inappropriate for the range of functional limitation many patients experience. Other game console platforms have also been explored in rehabilitation settings (e.g. Sony Playstation Eyetoy and Microsoft Xbox) however all suffer the same limitations. Video game console input devices (wands, joysticks, camera systems etc) may be insufficiently sensitive to the range of movement limitations associated with injury. The relatively "closed" nature of development environments for these platforms also makes it very difficult to program games that are appropriate for patient populations. The Microsoft Xbox is easier to program however Microsoft limits its development of the controllers to a non-physical paradigm such as the camera-based Project Natal. the Sony Playstation Eyetoy and more recently, the Playstation Move, are also restricted to camera-based interaction with the game console. In our project we focused on the Wii controllers, which we have explored in other projects, as it provides a relatively cheap way of connecting inertia-based motion sensors to a computer using dedicated software for the translation. We are also able to break out the switches from inside the Wii controller relatively easily (Figure 6).

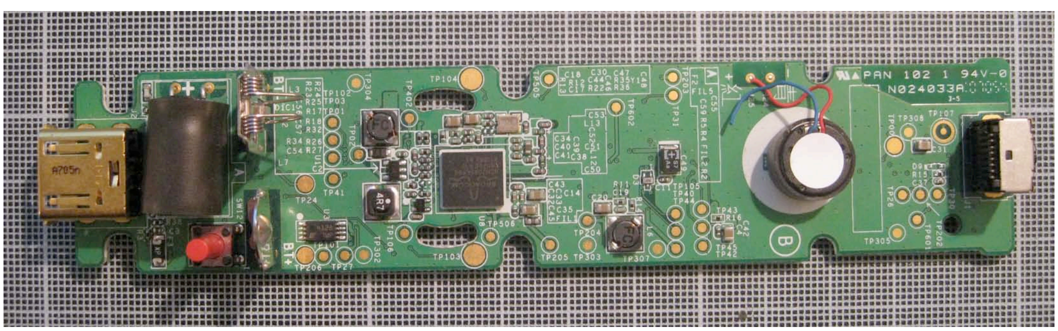


Figure 6. The inside of a Wii Remote

In this section the technology of the Wii controllers is described, as a basis for the adaptations developed in this project. The Wii Remote (WiiMote) has a three-axis accelerometer (measuring acceleration in the three lateral DoF's, and simultaneously two of these axes translate into tilt sensing: two rotational DoFs: roll and pitch) responding to gravity), an infrared camera based pointing angle tracking (two rotational DoFs: yaw and roll), several buttons, and sound and haptic output.

The WiiMote can be extended with the Nunchuck (containing a 2 DoF joystick and 3-axis accelerometer), and a MotionPlus gyroscope-based precision sensing unit, with sensors that measure speed of rotational DoF's (angular rate). The Wii Balance board used for the Wii Fit games has four force sensors (based on strain gauges measuring mechanical deformation of metal rods) with a range of 0 - 150 kg, and is about 50x30x5 cm in size. It can measure the weight and centre of balance, essentially two rotational DoF's (roll and pitch) isometric force sensing. Both of these devices communicate wirelessly with the game console using Bluetooth. They are battery powered, for our research we use rechargeable batteries.

For the instrumentation and the newly developed interaction appliances we can also use sensors, actuators and interfaces such as inertia based accelerometers (e.g. Figure 7), gyroscopes, resistive bend sensors (AGE), force sensors (Interlink, Flexi-force), QProx proximity sensing technology, Sharp infrared ranging proximity sensors, ultrasound distance sensors, camera detection systems and algorithms (including infrared or visible light beacons), switches, speech recognition, RFID (Radio Frequency Identification) tags and readers, and repurposed standard input devices such as Wacom tablets etc. A number of these sensors and interfaces are now readily available and can be easily connected to our Max/MSP-Jitter programming environment, such as Phidgets, Arduino, and Sparkfun modules. Max/MSP-Jitter is a graphical programming language for real time applications, very suitable for generating and manipulating data, sound and video.

Figure 7. An accelerometer for motion sensing used in the project

Exploration Phases

At the start of the project we identified three main strands for the exploration phase:

1) adapting existing Wii controllers to map the functional limitations of patients onto Wii game play,
2) instrumenting existing tools and devices currently used in rehabilitation, and
3) development of new, multimodal feedback interaction appliances for improved engagement with rehabilitation therapy.

Adaptation of Wii gaming perhipherals

We identified two main problems with the existing Wii Remote controllers; firstly there is a lack of adaptability in form and function, which prevents the device from being held at the right angle by SCI patients for successful game play, and secondly the buttons on the device are in a fixed position. This second problem is significant in that both the set up and game play phases of all off-the-shelf Wii games require button presses on the WiiMote. Simple button presses may often be impossible for the patient (button position out of reach, or muscle strength not available in that orientation) or the therapist (due to the button switches being covered by bandage). One proposed solution for the first problem is the development of a WiiMote modification, which would enable it to be worn at different angles within the range that is possible for the patient, and would also allow for button presses when the patient is using it. This may involve a stripped down version, removing case and separation from battery pack to create a smaller device to work with. There are now ‘clone’ devices available which have different form factors which may lead to new opportunities but these have not been tested yet. Their reliability has been questioned, particularly for the counterfeit ones. Some commercially available solutions for adapting WiiMotes exist, however these often remain limited and can be prohibitively expensive.

A second kind of Wii peripheral currently used by the rehabilitation facility is the Wii Balance board. By playing Balance Board games it is expected that SCI patients will develop core strength and control by balancing the upper body during gross movements in left-right direction as well as forward and backward movements. The use of the balance board was observed in the rehabilitation ward, and several problems were noticed. First, simply using the device took extended effort for both patients and therapist staff, as the patients usually had to be craned from their wheelchairs into a sitting position on top of the balance board, which in turn had been placed upon a standard a chair. This obviously limits the ability of using this tool on an ongoing basis in either the clinical situation or eventually the home environment once a patient is discharged. Additionally, transmission of the movements from the seated patient onto the four corner sensors was severely limited, reducing the impact that the player could have upon the game play. These issues can be addressed through a board that should allow an entire wheelchair to be placed upon it (see below). The extent to which this modification works will depend of course on the mobility of the client's core muscles.

Instrumentation of existing rehabilitation tools

The rehabilitation ward of the Prince of Wales hospital has many modular tools employed by the occupational therapists working with SCI patients. These tools, some of which can be seen in the Figures 8-12, were studied in the early stages of this project. The tools support development of dexterous manipulation tasks (for instance through turning a number of screws on a board), pulling little objects stuck with Velcro to a board, squeezing spring-loaded objects, moving and reaching objects of different weight, texture (slippery or rough), or fragility. Common practice is that these tasks and tools are prescribed to a patient as the therapist sees fit, and develop over the course of the therapy. The tasks with the existing tools can all be described using the Physical Interface Design Space framework (Bongers & Harris, 2002), as the tasks involved in using these tools involve manipulations in the range of movement and amount of haptic feedback along all axes of 3D space.

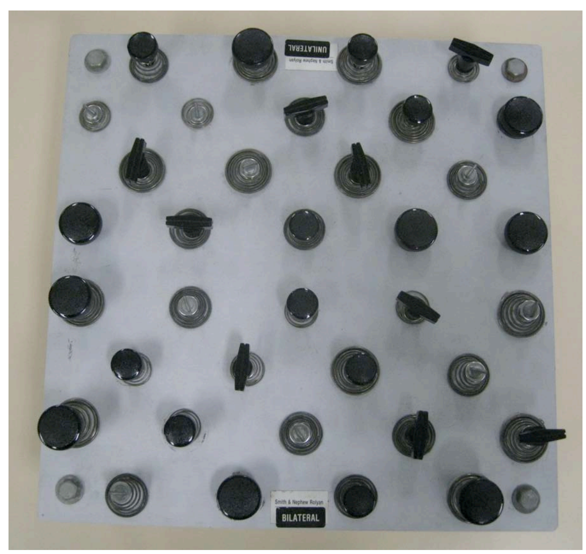


Figure 8 and 9. Rehabilitation tools for fine dexterity

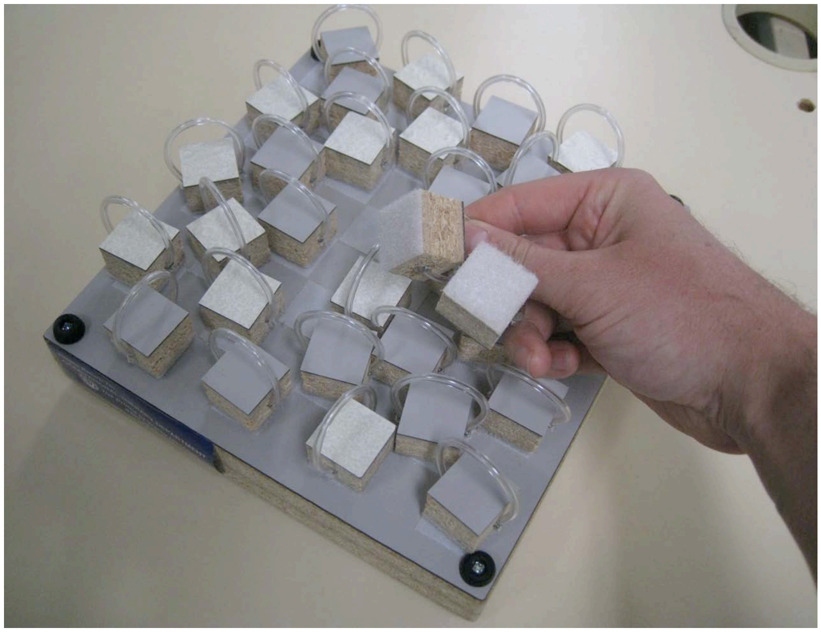


Figure 10 Rehabilitation tool for training pulling forces with velcro

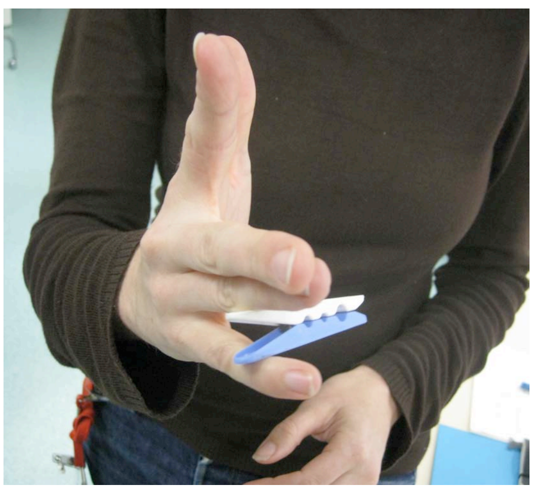



Figure 11 and 12. Demonstration of rehabilitation techniques combining dexterity and force

With these standard rehabilitation tools, objective monitoring of the patients progress is not possible. Often the therapist will ask a patient to attempt a particular task, then upon observing difficulties or success with that task will suggest another task that can help to focus in on where the rehabilitation difficulties lie. For example, the patient may have strength difficulties, or there may be muscular stiffness preventing the desired movement. Upon completion of several tasks the therapist will offer some practical activities to aid in addressing the issues he or she has observed. During our own observation of therapy sessions, the therapists indicated that they can not know exactly how their recommendations have affected each particular patient over time. We propose that more objective measurement of movement function during therapy could potentially lead to a better feedback system for therapist and patient.

Traditionally, standard tools of rehabilitation offer the therapist the flexibility required to test the various limitations of a patient's particular rehabilitation needs, and inherently offer methods of improvement of interactions with objects that are typically encountered in the activities of every day living. A range of techniques for 'instrumenting' these tools are being investigated, which include the addition of sensors that enable a computer programme to generate visual, auditory, haptic or game-based feedback.

It is envisaged that by integrating layers of interactive technology with existing rehabilitation tools, therapists and patients will be able to easily adapt their practices without changing their routine, and still gain from increased feedback mechanisms. Currently we are developing a range of techniques for 'instrumenting' these tools, by adding sensors for input signals to a game or other feedback and representation systems (see below).

New interaction appliances

There are limitations imposed by commercially available game controllers described in a preceding section that cannot be solved through simple modifications. To overcome the inherent limitations of mappings in the controller - game-console relationship, we decided to explore the possibility of designing new interaction interfaces that are more appropriate for the functional requirements of rehabilitation. Rather than adapting existing video game hardware, our approach was instead to create new environments with visual, auditory and haptic feedback in response to the therapeutic movements of the patients. To emphasise the two-way and multimodal nature of these interfaces, the term Interaction Appliances is used.

This part of the research applied our existing knowledge and wide ranging toolkit of (wireless) multiple DoF motion sensors, force sensors, proximity sensors and physical objects. We also built upon previous insights and design skills we have acquired in the development of new musical instruments, interactivating objects and tools, as well as sound synthesis techniques. Using the interaction techniques as developed and applied in Interactivation Studio projects (motion sensors, force sensors, wireless connections, etc.) gave us significant design freedom and flexibility. Our development of interactive games and multi-levelled feedback mechanisms was performed using a combination of different software tools for particular purposes; Max (mapping), MSP (sound), Jitter (video), and Processing (visualisations). Processing is an open source programming language, very suitable for data and process representations and environments (Raes and Fry, 2007).

The ability to freely track, guide and analyse the multiple DoF movements of the functionally impaired patients is essential for suitable rehabilitation therapy. We did not want to constrain the movement patterns of patients to fit with any restrictions imposed by measurement and sensing technology. The Wii controllers themselves reveal too little about the complex motions that are part of the therapy and therefore rapidly become limited in their usefulness for rehabilitation. Similarly for video camera based systems such as the Playstation Eyetoy and Microsoft Natal where the complex three-dimensional movement patterns of human limb movement are very difficult to extract from essentially a 2D representation. Furthermore, often articulation of the human movements demands simultaneous tracking of multiple DoFs of several body parts. By using distributed sensors it is possible to track the movements appropriately, and allow for the generation of guiding / rewarding / training feedback for matching and improving movement trajectories. Our approach also enables the objective measurement and storage of these movement trajectories. As a consequence, therapeutic specialists will be able to acquire longitudinal data concerning progression of rehabilitation for their patients, This data could be used to inform the direction that subsequent rehabilitation takes or enable tracking of performance once a patient leaves hospital and returns to their home environment.

Design Solutions and Outcomes

In this section the iterative process of our development cycles for each of the three strands (Adaptation, Instrumentation and new Interaction Appliances) are presented. Over a period of two months, members of our design team visited the spinal rehabilitation ward of the Prince of Wales Hospital and observed therapeutic sessions in the rehabilitation ward, conducted interviews with therapists, researchers and patients. We then developed prototypes in the UTS Interactivation Studio based on these sessions followed by an iterative cycle of test, redesign and retest to create solutions for application in a rehabilitation setting. the following

Adaptations

Using the adaptation approach described above we first modified and tested a WiiMote for use by a spinal cord injury patient. The WiiMote unit was opened and wires were soldered to the switch contacts on the circuit board, bringing out the A and B switches through small external connectors (3.5mm mini-jack) as shown in Figures 13 and 14.

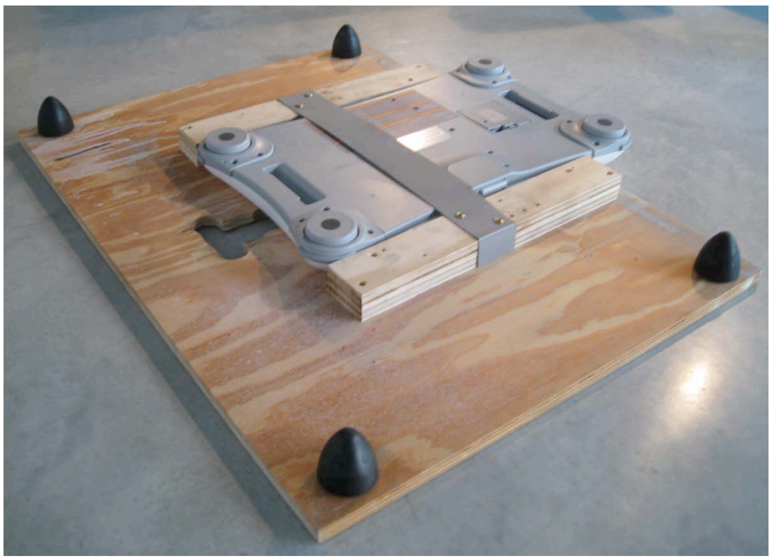
Figure 13 and 14. The modified WiiMote and switches that can be connected

The modification was successful - the patient who joined the team was able to play several games with the button switches operated by his elbows. This patient reported that one of the “most crushing things” about suffereing SCI was that he would not be able to play video games again. By providing him with a modified WiiMote controller we were able to enable him to play video games once again.

The connectors we attached to the WiiMote fit the range of existing commercial rehab-switch solutions, big switch pads that can be mounted on the side of the wheelchair (Figure 15), on the shoulder of the player, eye-brow switches etc. For further improvement the "home" button, which is used to exit from games or navigate through menus, could also be extended in this way. The "plus pad" four way switch has been identified as necessary for some game play and could be connected to larger rocker switches at the side of the head, or extended mechanically with a small perpendicular rod acting as a joystick.

Figure 15. Wii game operated through an external switch operated by the elbow

The Nintendo Balance board was adapted to address the issues outlined earlier, enabling a chair or even wheelchair to be placed on the board. It consist of a piece of 16mm thick plywood expanding the top surface of the balance board to about 80 x 60 cm. The Wii Balance board is mounted in such a way that it can slide to find the optimal position. The battery compartment is covered in some positions, this is not a problem because a rechargeable battery pack is used so it doesn't need to come out. There are four rubber silent blocs mounted on the corners to prevent the tipping of the board should the centre of gravity be too far off, whilst continuing to transmit movement to the board's sensors. Plywood ramps enable the wheelchair to be rolled on top of the structure (Figures 16 and 17).



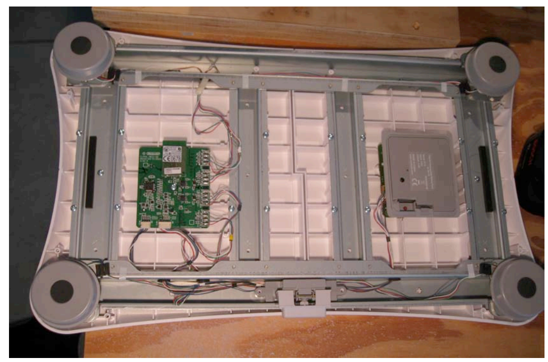


Figure 16 and 17. Wii Balance board extended construction and internal connections

The first tests of this adapted balance board showed that with a small amount of calibration a light wheelchair (we tested an 8kg chair) can be used in a set up with the Nintendo WiiFit game. The system was set up to respond appropriately according to the movements of a novice user. However, the balance of a person in a wheelchair is different from the balance of a person standing on their feet. With the large base of the Nintendo Balance Board measuring 50 cm across, the left to right movements (roll DoF) of the patient had only a limited affect on the movement of the in-game character. This limitation resulted in the patient using "cheating" by gripping his wheel chair with his hands, resulting in less than desirable rehabilitation outcomes.

This limitation of transmission was then addressed in a second prototype were the orientation of the balance board is rotated such that the narrow dimension (30 cm) is used for the left-right orientation. To do this we swapped the corner sensors of the Wii Balance Board by changing the internal wiring, so that it appeared to the Wii console as the normal mapping. This is a good example of how cumbersome the changing of the Wii mappings is, if at all possible. In our final modification of Wii Balance Board use (Figure 18), the transmission of movements is greatly increased in the his left-right direction (roll rotational DoF) which has been observed in the initial games of WiiFit as being the most used. These movements are also safer for the patient, as many patients have limited strength in the central core muscles, only being able to lean forward to approximately 15 degrees.

Figure 18. A patient playing a Wii Fit game using the modified balance board

Instrumentation

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 aim of this task is that the patient can improve their ability to interact with everyday objects in the home. We therefore developed instrumentation that augmented the existing rehabilitation tools and enables patients to carry out such a reaching task with enhanced multimodal feedback.

Using an instrumented object (plastic tube similar to what is normally used for reaching tasks), containing an RFID tag, motion sensor (Phidget USB 3-axis accelerometer) and haptic feedback unit, the patient carried out a reaching task (Figure 19). The targets contain an RFID reader (Phidget), connected via USB to the computer running an Max/MSP programme which generates the multimodal feedback. 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, and good quality studio monitors (Genelec A8020 active loudspeakers).

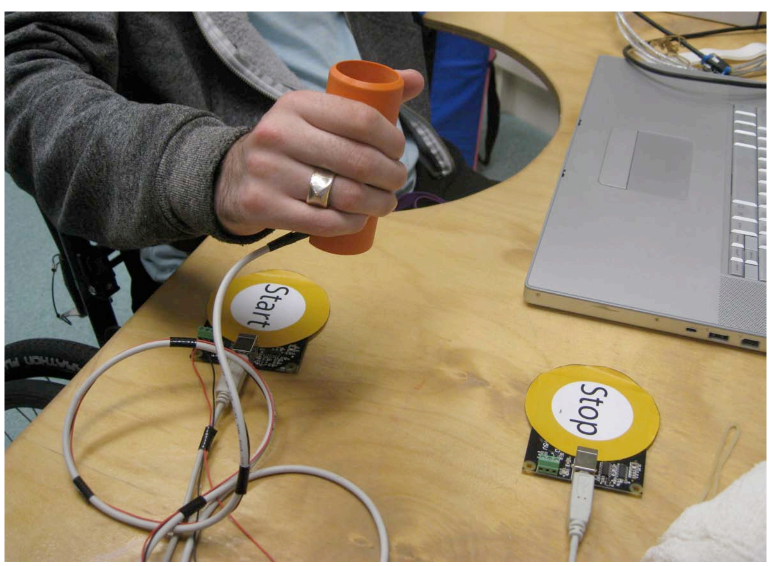


Figure 19. Variable reaching task with computer-generated feedback

Interaction Appliances

After discussions with rehabilitation specialists and therapists, we realised that there was a need for a rehabilitation tool with a multitude of targets, possibly distributed not only on a flat surface but also in three-dimensional space. To fulfil this requirement we designed our tool such that the RFID reader was contained within a device that the patient could move around in 3D space while the static targets contained the RFID tags. As the RFID tags are inert and have no power requirements, they can be placed at any of a number of locations in 3D space (Figure 20) and attached to any object that a patient may be required to interaction with.

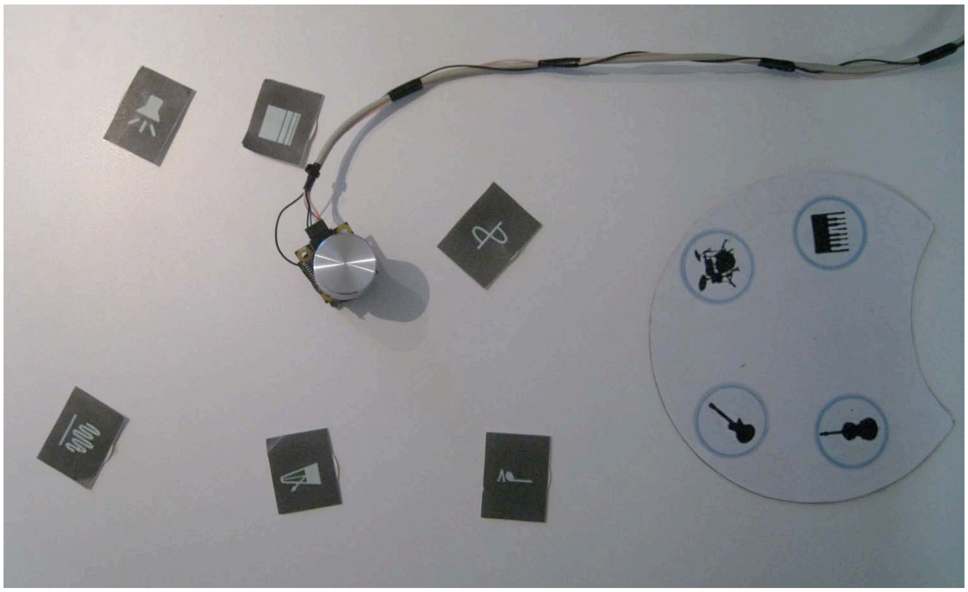


Figure 20. The interactivated objects and icons of the musical task

We have designed two prototype interaction appliances, one is a wireless RFID reader (Figure 21) and the other is a wired (USB) combination of an RFID reader (ID Innovations, using RS-232 connected through a virtual serial port), Phidget rotary encoder and a Sparkfun vibrotactile feedback element. These appliances were developed to control the parameters of an algorithmic music making programme, Jam2Jam (Brown et al, 2009). We developed an interaction style where the user selects first the instrument (bass, drums, guitar or keyboard) and then the parameter to modify (such as tempo, pitch, timbre etc.). With the rotary encoder (with a big turning knob) the parameter value can be set instantly.

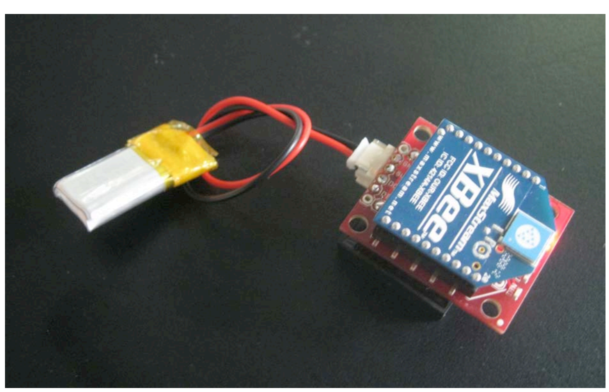


Figure 21. The custom built wireless RFID tag reader

The use of tagged objects allow the therapist and patient to place the reaching goal at any location in a three-dimensional training space. In our preliminary design stage, the rehabilitation training task using the technology we have developed is relatively ope-ended such that there are no time constraints placed upon the patient for completion of the task. In subsequent versions the training task can be extended with a timing or test regime and measure proportional changes in ability.

Our rehabilitation tool was tested in the ward with a patient, who was asked to participate in a task changing the musical parameters of the Jam2Jam application. This way a reaching task with variable dimensions was incorporated in a music making activity. It was initially observed that it was hard for the patient to grasp the moving objects, particularly the wired one as the USB cable interferes with the movement and the object is heavier. The wireless device was significantly easier to handle, however a lighter battery would be beneficial for future use. We also changed the shape of the object by adding ridges around it, facilitating a better grip (Figure 22).

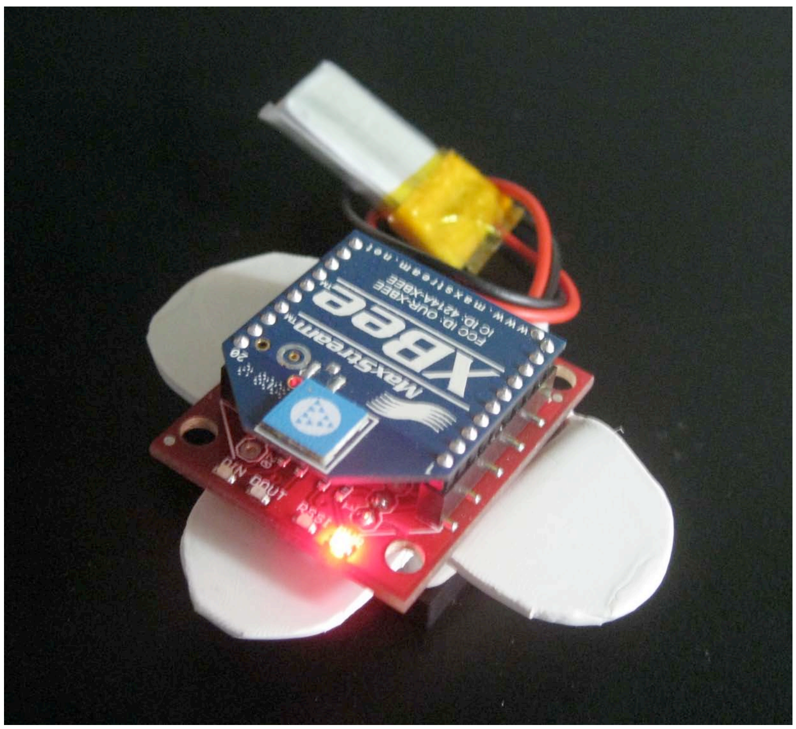


Figure 22. The modified shape of the wireless RFID tag reader

Another common task that seemed appropriate to rehabilitation is to facilitate handwriting training. We conducted an investigation using a Wacom drawing tablet, where the DoF's of movement of a stylus were mapped to musical parameters, thus enabling the patient to practice a set of movements related to the handwriting task (Figure 23 and 24). The position of the pen (stylus) on the surface was mapped to sound volume (up / down or y-axis translational DoF) and stereo panning (left / right or x-axis DoF). The parameter that controlled most features of the interaction was the tip pressure (z-axis isometric DoF) which was mapped to the playback speed of the music. Moving the stylus around and applying the right pressure resulted in the correct playback speed of the chosen song. For the test the sensitivity of the stylus tip was set appropriately in collaboration with the patient. The shape of the stylus was modified, to allow an easier grip for the patient as can be seen in Figures 23 and 24.

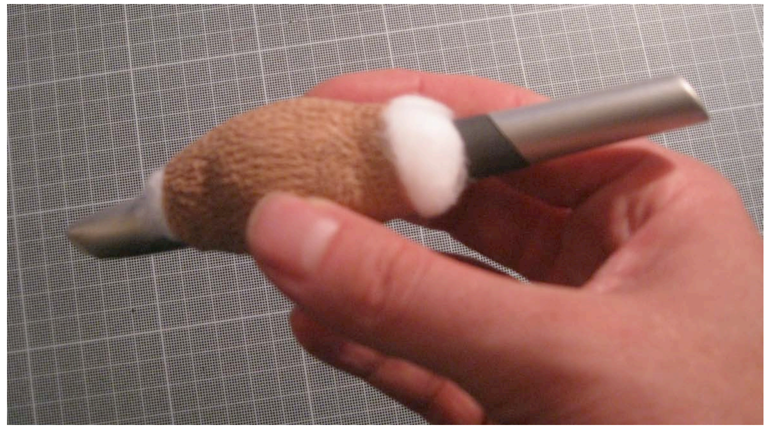



Figure 23 and 24. Using a Wacom tablet as an input device for a musical task, and a close-up of the modified pen for better grip.

CONCLUSION AND DISCUSSION

Overall we received very positive feedback both from patients and therapists regarding the interaction with the technology we developed for them. In joint discussions with both patients and therapists many new possibilities and ideas for extension of the technology were raised, adding to the richness of this exploratory research endeavour.

The purpose of the project discussed in this chapter was to cover the explorative phase of research for subsequent investigation of the efficacy of multimodal feedback for rehabilitation of movement impairment following SCI. In a relatively short time frame we achieved a fruitful exploration of the issues at hand, by rapidly developing prototypes and demonstrator devices. Many possibilities for future development of rehabilitation technologies have been opened up, and from the experiences and results from this explorative phase we intend to select one promising area for further investigation. The next phase will need only a short development period based on the findings presented in this paper, facilitating setting up a pilot project. The next phase is to set up comparative tests with multiple users, patients who will participate in both traditional therapy as well as the enhanced versions, using new interaction appliances and instrumented tools allowing for multimodal articulatory feedback and representation. We hypothesise that the increased level of interaction with engaging, multimodal feedback rehabilitation tools will lead to significant improvements in patient performance compared with tradition rehabilitation interventions. Our team at the Prince of Wales Medical Research Institute has significant expertise in running randomised control trials to investigate the efficacy of behavioural interventions in the medical domain.

It is important that the parameters of each interactive feedback tool we develop can be easily altered by both the therapist and patient. This can be performed through control elements that are designed as part of the interaction appliance. These control elements can be sliders, dials and buttons rather than settings hidden in menus of a graphical user interface. Because of the wide variety of patients' abilities, individual settings and customised training programmes need to be set up easily. Data logging techniques also need to be developed, and the rehabilitation tools need to be robust and portable so that patients can work with them away from the ward, possibly even in their own homes. It should also be possible to use the tools for long periods of time without failure and without the patient becoming overly familiar or bored with the tool itself.

We are also interested in application of our technology to rehabilitation of patients with functional impairments caused by conditions other than SCI. For example, there is an increasing awareness that functional rehabilitation of limb and hand function is possible following stroke and with a wider range of rehabilitation tasks that may call for a larger variety of interaction appliance design. Examples of such technology include sensitive floors for acquiring information about gait for individuals with gait disorder (requiring reconfigurable, two-dimensional spatial resolution, force sensitivity) and further application of haptic feedback to address the tactual senses that are often impaired with SCI and stroke patients. By using design principals that encourage rapid prototyping and user feedback modification, it is possible to design rehabilitation tools that will further ensure patient compliance with their rehabilitation routines. In this way we can map the interest set of the patient onto the particular instance of the rehabilitation tool we provide, for example, if a patient is interested music then we can design a rehabilitation tool that has a musical theme (Figure 25). By developing interaction devices that also use common design principals, it will be possible to apply the interactivation design approach to a wider range of patient groups leading to a great potential for creating solutions that can help people.

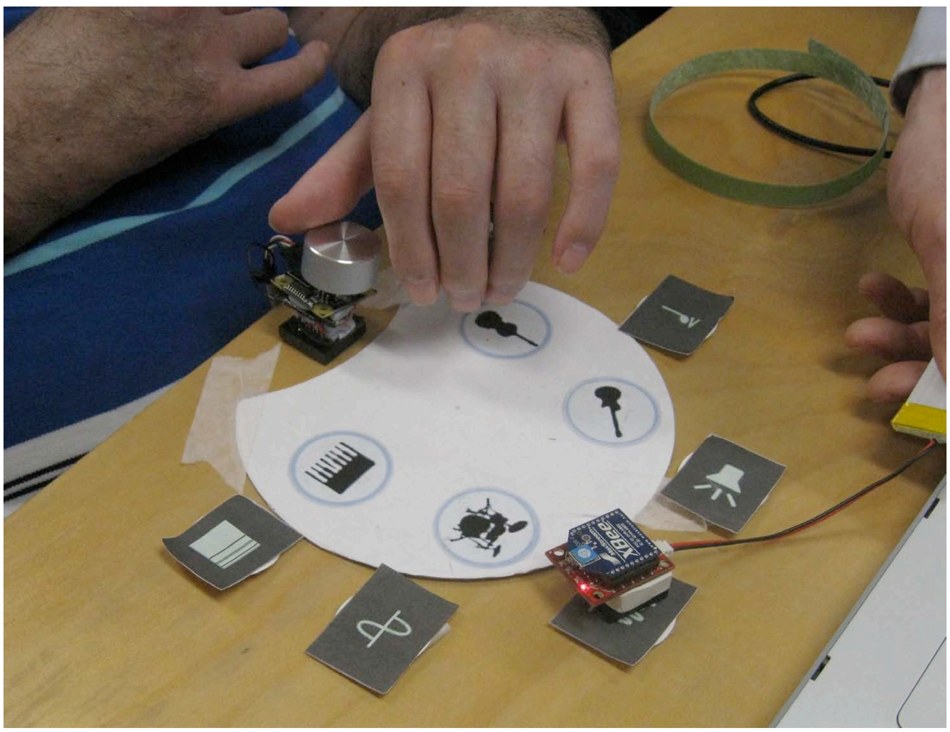


Figure 25. A patient training with a musically enhanced reaching task.

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We would like to thank the SCI patients and the therapists at rehabilitation ward of the Prince of Wales hospital for their involvement and their helpful comments and feedback.

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