Interactive interfaces for movement rehabilitation in virtual environments

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ABSTRACT

This paper discusses a system for movement rehabilitation that uses low-cost widely available input devices supporting force-feedback, enabling the design of an individualised therapy curriculum. Interactive 3D environments present tasks that can be adapted in terms of complexity and ease of goal attainment. The system is focused upon promoting increase in the range of movement, control of tremor, control of limb velocity and control of smoothness of movement. Our system exploits the use of augmented feedback to enable the patient to identify the strategies and sensory cues that support re-organisation of the impaired motor response. Stress is laid on flexible mapping between the limb movement and the virtual environment action; this provides an extensible system to cope with diverse movement (dis)abilities and also encompass advances in input device technology.

1. INTRODUCTION

The incidence of stroke is steadily increasing in the population of Europe and the USA. There is a high incidence of both cognitive problems and movement problems following stroke. The typical pattern of impairment in the motor system is loss of muscular control and impairment of muscular sensation on the side contra-lateral to the site of damage (hemiparesis). The degree of hemiparesis and its topology will vary between individuals, but some general patterns of dysfunction may be evident. Limb control which is normally ascribed to the cortico-spinal, pyramidal tract (e.g. fingers, lower limb) is often impaired, whereas more proximal areas may be less profoundly affected. It is therefore common for patients to exhibit problems with manipulative movements, on the contra-lateral side, following unilateral stroke. The lower limbs may also be affected and because effective balance and locomotion requires co-ordination of both lower limbs, there may be a general disruption to gait and standing balance.

There may be some degree of recovery of function during the first 6 months, which does not seem to be dictated by the type of therapeutic intervention. This generally follows a negatively accelerating curve, such that rapid and 'promising' improvement may be seen in the first 3 months, but if no intervention is introduced this will plateau at a level well below what is optimal. The role of therapy, therefore, is to enhance the degree of recovery and to try and avoid an early plateau in the degree of functional recovery. Whether this goal can be met by many conventional therapies is a matter of debate (Pomeroy and Tallis, 2000), but there are reasons why this is not a simple question to address. Firstly, it is not clear how goal achievement should be measured and whether the return of 'normal function' precludes atypical patterns of movement (Latash and Anson, 1996). Secondly, the efficacy of a specific therapy does not rest solely in the procedures and principles of the method, but on the cognitive, emotional and social factors that accompany the patient (Maclean and Pound, 2000). Motor learning following cortical injury is a considerable challenge that requires a steady re-learning of what had previously been everyday skills. The majority of grounded therapeutic procedures require the repetition of simple actions and improvement may be slow. Coupled with this a rehabilitation ward may not provide a particularly engaging environment. Walter and Kamm (1996) have suggested that it may even be negatively disposed to learning: 'individuals with movement disorders begin resolving the priorities of their pathologic sensorimotor system while the niche that they occupy (e.g., acute care hospitalisation) is perceptually, motorically, and functionally impoverished'. Even outside of the ward, the tasks presented to outpatients may not provide them with a stimulating and fulfilling set of activities. A study by Newall et al (1997) recorded that the amount of time spent by a patient on 'homework'

and active recreation accounted for only 1.7%-5.4% of a 24-hour period.

Computer assisted or 'virtual environment' systems have a potential role in enhancing the rehabilitation environment and the procedures or tasks that are presented to a patient. We describe a system that provides a user with the facility to practice skilled movement in virtual environments:

The system is adaptable to user abilities to provide access even when residual movement abilities may be poor. The user can benefit from practising tasks, and achieving goals, with their residual motor control that would otherwise be impossible.

Secondly the system has the potential to be used in domiciliary rehabilitation and therefore make the transition from hospital-based to domiciliary rehabilitation more seamless. Whereas the use of rich, task driven, computer-generated environments may help to offset the tendency for outpatients to neglect their 'homework'.

A third benefit is that tasks for such a system are designed once and used many times, with the implication that if a task designed at one centre seems particularly effective it could readily be distributed to other rehabilitation units. This could lead to a more standardised, or repeatable, therapy curriculum with best practice becoming embedded in the task design over time.

The system is not seen as a substitute for hands-on therapeutic input, but a supplement, where a therapist/clinician can set an individual task, which the patient can practice, without direct supervision. Clinicians are not required to guide the user through the task, or provide feedback – though additional input might be given – freeing them to focus on patient progress and strategies on further intervention. Additionally, the system can provide data on progress for individuals that may be collated across the recovery period or across individuals to provide a database on patient progress.

Despite the promise of virtual interfaces for rehabilitation there are a considerable number of questions that arise regarding what a system should encompass, what should be excluded and how the system might be tuned, or adapt, to individual patient requirements, without becoming so diffuse that it requires on-site programming support.

2. RESEARCH IN MOTOR LEARNING

2.1 What aspects of motor control?

There is a wide range of disorders that have a major effect on motor system functioning, such as Stroke, Cerebral Palsy, Parkinson's Disease and Multiple Sclerosis. There are generic manifestations of such pathologies, however, that arise from the neurophysiology of the motor system. The dysfunction resulting from *Cardio-Vascular Stroke*: has already been outlined and is typically a loss of muscular control and the impairment of muscular sensation on the side opposite to the site of damage, particularly with respect to hand and finger control or control of the contra-lesional foot. Muscular weakness in stroke may in some case progress into spasticity.

Congenital Cerebral Palsy occurs in approximately 0.1% of live births, although the incidence may rise to 4% amongst very low birthweight infants. The children first exhibit hypnoticity (a lack of muscular tone), but this eventually becomes a pattern of either spasticity (hypertonicity) or athetosis (involuntary limb motion) or both. The problem is fundamentally different from that of the stroke patient, but the resulting difficulty in tackling everyday tasks share similarities

Parkinson's Disease arises due to a degeneration of the substantia nigra and a subsequent drop in neuro-transmitters leading to a breakdown of the functions associated with the basal ganglia. The resulting problems may be rigidity, tremor and slowness of movement (bradykinesia), although drug therapy may also result in involuntary movements that are behaviourally similar to athetosis.

Multiple Sclerosis arises due to a degeneration of the myelin layer in the CNS, the consequences may be visual deficits and problems with limb sensation and muscular weakness. The problems may be first evident in the lower limbs, but upper-limbs are also affected. Once again, although muscular weakness (hypotonicity) is a primary sign, spasticity (hypertonicity) and tremor may also develop.

Generic Features: Hence although we can identify different causal mechanisms in the examples above, the motor system response shares the common features of either: hypotonicity, hypertonicity or involuntary movements. The behavioural consequences are muscular weakness, rigidity, tremor, spasticity, athetosis and these can be considered as generic symptoms of motor pathology that undermine skilled action.

We could adopt the view that these are irreversible dysfunctions of the motor system and that the CP or post-CVA individual will never re-attain adequate function in the affected limbs. There is evidence of neuronal plasticity, however, that suggests re-learning should be possible even when there is damage to areas that are associated with a specific function for an intact motor-system. On the general issue of environmental exposure, Schrott (1997) examined the effects of environment and training on brain morphology. Brain weight can be affected by environmental conditions; more specifically most studies show increases in forebrain and cortex. Environmental conditions can alter dimensions of the brain (e.g. thickness, height, length, width) though changes appear to be more dependent on the duration of and the time at which the environmental manipulations are applied (Schrott, 1997). Specific peripheral inputs can affect corresponding central structures in humans. Elbert et al (1995) provided evidence that string player have increased representation of their left hand in the primary somatosensory cortex. Whereas studies with genetically identical animals provide evidence that brain anatomy may be altered by intellectual challenge. What is unclear is how much change can be elicited, the time frame for such changes, and the degree of compensation they provide (Schrott, 1997).

Table 1.

Motor Disorder	Functional impairment(s)
Hypotonicity	Muscular weakness, restricted range of movement (RoM), poor velocity control.
Hypertonicity	Severe restriction on RoM, unpredictable muscular contraction, jerky movements
Athetosis/Dyskinesia	Unintended actions, poor kinaesthetic sensitivity
Tremor	Poor stabilization, unreliable positioning, lack of smoothness.

2.2 Why a virtual environment?

If we accept that there is plasticity in the CNS (Nudo and Friel, 1999; Liepert et al, 2000), then there is potential for the motor impaired user to re-attain function if the environmental conditions are conducive to learning. Although progress in motor function ultimately requires a change within the individual, that change is stimulated and fashioned by the information received from the environment. The sensory feedback (visual or haptic) that arises from an action, and the knowledge of goal achievement (or failure), are essential in guiding the re-organisation and re-acquisition of skill. But how can an environment be fashioned to optimise these factors? What tasks, settings and experiences should the patient be exposed to?

Our perspective is that ultimately, the patient needs to pass through stages of re-exploration to identify strategies of control that are effective for their disturbed motor system (Wann and Turnbull, 1993; Wann et al, 1997). These stages can be viewed as constructing a *forward model* for motor control and an *inverse model* for goal achievement (Wann et al , 1997). Following cortical damage the patient/child is faced with both a new mapping between the central nervous system (CNS) and the actuator (e.g. limb, mouth) and a new mapping between a weakened/spastic limb and the environment. A *forward model* represents learning from sensory feedback about the effect on limb movement of specific motor commands. An *inverse model* is an identification of the motor commands required to produce a specific response, hence it requires information about goal achievement in addition to intrinsic feedback. The latter therefore requires a learning environment beyond the level of conventional biofeedback. An optimal learning environment should be one that allows the patient to practise limb movements, while providing rich feedback as to the errors of movement and potentially provides some guidance toward goal achievement. The advantage of computer generated environments for meeting these goals is that the patient can attempt tasks at their chosen pace and the task can be tailored to their individual level of expertise. A VR setting can provide real-time feedback of errors to the patient and provide feedback on range of movement, trajectory straightness, trajectory speed, smoothness and accuracy. What is required are environments that can guide children/patients in attempting to produce more refined movements, and highlight the errors they make, to enable them to recognise the efficacy of their attempts at movement (*Forward Model*) and identify the effective strategies for intended actions (*Inverse Model*).

Embedding the task into a stimulating games format may provide a motivational drive towards the patient engaging in extended practice in a guided-learning setting. Maclean and Pound (2000) propose that giving patients control of their goals may help in motivation. The goals set by rehabilitation staff may be seen as too ambitious or not ambitious enough: "An understanding of all the factors which impinge on motivation will also empower rehabilitation professionals to better cope with the phenomenon of patient disengagement with rehabilitation...and can only have positive effects on patient care" (Maclean and Pound, 2000). It is difficult to predict what will be motivating for a patient coming to terms with major motor dysfunction. Regular contact with therapists and clinicians who show interest in individual progress probably provides the

strongest motivation. Embedding therapeutic exercises into a games format cannot be a substitute for this, but can enhance the feeling of goal achievement and progress, even if the goals achieved are relatively minor. Related motivational effects can be observed in adherence to exercise with the normal population (Annesi, 1998) and the growth of feedback systems for exercise machines (heart rate, calories burned) subscribes to a similar theme.

2.3 Feedback and intensity – or When? What? Why?

Winstein (1991) suggested that the knowledge base in motor learning can be used to provide at least partial answers to a number of clinically relevant questions – such as, what kind of feedback is best for motor learning or how often should the therapist provide feedback during a treatment session? It should be noted that this view was based on the assumption that the principles of motor learning for patients with orthopaedic and neurological disorders are similar to those of healthy individuals. Hartveld and Hegarty (1995) proposed that the challenge for both therapists and patients is "to encourage the development of intrinsic feedback cues in order to control more complex tasks and to decrease reliance on feedback equipment, while at the same time providing just enough augmented feedback to maintain motivation and the desired movement pattern". One proposal is to provide the performer, or patient, with control over the form, quantity and timing of feedback, the practice schedule, and the level of assistance. It has been suggested that allowing patients control over the use of assistive devices and feedback may be particularly beneficial (McNevin et al, 2000)

Different options for the type of feedback arise from the research literature, depending on the motor task and end goal. Frequent feedback seems to speed improvement in task performance, but retention and transfer appear to be adversely affected. Other options are; bandwidth feedback where the performer is only given explicit feedback when their performance varies sufficiently from some preset ideal; delayed feedback where a delay is inserted between task completion and feedback presentation; and various distributions of feedback within trials (e.g. faded feedback). Bandwidth feedback appears to aid performance consistency.

Finally there is an issue as to what aspects of the task should be informed by feedback. There is evidence that if a performer's attention is directed to their own movements the execution of automated skills can be disrupted and the learning of new skills degraded (McNevin et al , 2000). Therefore presenting tasks where the performer is rewarded for task achievement without an explicit focus on their movements may be advantageous. This suggests that *feedback* given to performers during practice may be most effective if it directs their attention to the consequences of movement, rather than to the movements themselves.

There is also debate regarding the intensity, or frequency of practice. Is an increase in the intensity of therapy better? The majority of studies examining the value of increased therapy have used a different type of therapy as the additional quotient. This raises the issue of whether it is the additional therapy time, or the additional therapy type, that is of most benefit. There is some evidence that the addition of more time on the same programme may not reap additional gains (Lincoln et al, 1999), but the addition of time with a different programme may be beneficial (Feys et al, 1998; Sunderland et al, 1992). Additionally therapy may only be effective for less severely impaired patients due in part to the stress or inconvenience of the additional load (Parry et al, 1999). In a study of examining the benefits of increase intensity on arm function following stroke ~17% of the participants did not complete the extra treatment, as they could not tolerate the extra treatment (Lincoln et al , 1999).
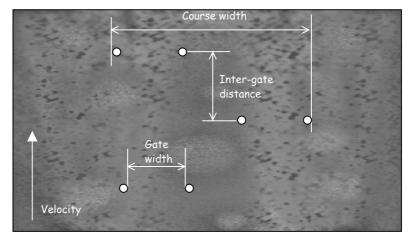
2.4 Motor learning and the issue of transfer

A recurrent issue with the use of virtual environments for training is whether there is likely to be transfer to real world tasks. There is evidence to support the transfer of training in virtual environments to real world environments (Rose et al, 2000; Todorov et al, 1997). Rose et al (2000) also found that training in virtual environments 'was less influenced by the introduction of interfering tasks' compared with real world training. In the case of therapy, there is a general issue as to whether any specific set of exercises will transfer to a functional improvement in activities of daily living (ADL). Although a VE could be used to simulate ADL, there is limited utility in creating the 'virtual kitchen' and 'virtual bathroom'. The major benefit of VE-ADL is at the level of cognitive rehearsal, procedural memory, sequential planning. It is currently not viable to try and simulate the perceptuo-motor consequences of picking up a full teapot. The goal of the VE system should be to breakdown the task, such that simple components of motor control can be practised that will eventually support the challenging task of picking up a real, full teapot. Our approach it to focus on a set of simple motor tasks that address functional problems that arise across a number of cases of motor impairment (Table 1). It is assumed that providing environments that encourage practice on range of movement, speed and smoothness of movement, and anticipation of external forces, will provide the building blocks for more complex skills.

3. THE ARL SYSTEM

With reference to table 1, the aim was to present tasks that progressed from simple goals, such as increasing the range of movement (RoM), to more subtle aspects such as moving through the range smoothly and at speed. We therefore concentrate initially on 4 factors relating to the kinematics of movement: *RoM; End-point accuracy; Speed of movement; Anticipatory timing.* To embed these task parameters within a game environment we have used a slalom-like task where a choice of peripheral input devices may be used to translate the viewpoint left-right in the virtual environment. The viewpoint has fixed velocity during a trial, and the goal of the environment is to pass through as many gates as possible on any given course. Several parameters can be changed within the environment as illustrated in figure 1.

Figure 1. *Changeable parameters within the slalom task.*

Varying the *course width* changes the *RoM* goal for the user, whereas changing the gate width changes the *end-point accuracy* requirement at the extremes of the *RoM*. Increasing the *forward velocity* has the effect of globally scaling the required *response speed*, whereas *inter-gate distance* scales the *timing* requirement. The course layout should be tuned to the capabilities of the patient, but the basic task components generalise to a number of tasks. The current system is being piloted with standard manual input devices such as a joystick,

but also with postural control tasks. In the latter case traversing the environment requires shifting weight between feet, with RoM relating to the percentage weight distribution. The ability to shift the centre of pressure smoothly and accurately between the feet is important for balance and gait. Hence repetitive practice of weight shifting is pertinent for a number of hemiplegic patients. The restriction on activities is primarily due to peripheral input technology. There are still relatively few input devices that are priced at a level suitable for the home therapy sector. When, or if, whole body tracking systems are developed for the games market, it will still be the case that the tasks presented to motor impaired users will need to be broken down into simple achievable sub-goals.

The mapping between input device and the environment is essentially arbitrary. It could be considered that there are two goals: the therapist may have a particular movement goal but there is also a task goal. The task goal may be to translate vertically over a set of obstacles, but the limb/device movement may be a limb rotation. Within the task environment the goals can be considered to have some hierarchical structure:

Level 1: Range of Movement : End-point Accuracy - Course width : Gate width

Level 2: Response Speed : Response Timing   - Forward velocity : Inter-gate Distance

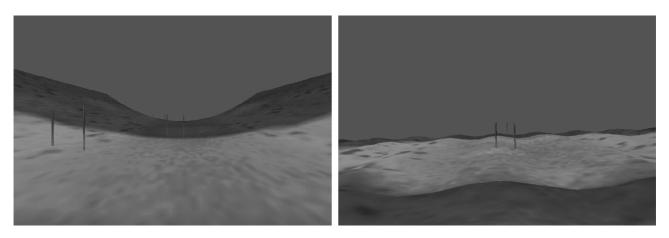Level 3: Working with/against external forces   - Terrain gradient

Figure 2. *The slalom task, with force feedback parameters Left: a force-valley Right: an undulating course.*

3.1 Integrating force-control tasks and haptic feedback.

The introduction of low-cost force-feedback joysticks and wheels (e.g. Microsoft Sidewinder, Logitech Wingman) has afforded the potential to introduce force feedback into the system. Within Level 3 we were concerned with providing predictable changes in external forces. To provide a visual correlate of the force field the force-feedback is coupled to changes in the terrain gradient, such that forces act in a direction commensurate with (virtual) gravity. Hence the environment in Figure 2-left requires movement against retarding forces to move upwards to a gate and the control of force-assisted motion away from the gate. This introduces a timing requirement in addition to that proposed in the preceding level. Level 2 introduces a requirement to anticipate the arrival of each gate and initiate an appropriate response. In Level 3 the user should anticipate that there are forces that may assist and resist a movement and in the case of Fig 2-left these switch mid-way through the trajectory. Maintaining a smooth and accurate trajectory in such circumstances requires anticipation and appropriate motor planning. Figure 2-right displays a challenging terrain that requires stabilisation against disruptive forces while moving between spatial targets.

3.2 Tuning the system

We can classify a system by the level of flexibility presented at the user interface. The least flexible system has a fixed interface that may be optimal for an 'ideal user' envisaged by the designer, but awkward or unusable for someone with differing abilities. *Customisable systems* offer the ability to modify the interface to suit the current user. *Adaptive systems* automatically alter aspects of the system to suit the requirements of individual, or groups of, users and their changing needs over time (Benyon and Murray, 1993). In order for a system to adapt sensibly to individual users, a model of the user is required. The system can gain knowledge about the user explicitly, or by monitoring user performance in a suitable task.

Given knowledge of the user there is the choice of either adapting the input to action mapping or the layout of the environment itself. For instance, in the case of restricted movement we can either increase the input gain or decrease the distance between targets within the environment. Changing the environment, rather than input-action mappings, may have the advantage that in-task adaptations may appear more seamless: two targets further apart rather than an increased gain in input should appear more natural. Information for tuning the system is recorded within three distinct models:

User Model: Holds knowledge about the user, either explicitly or implicitly encoded, which is used by the system to improve the interaction. This may be with co-operative agreement with the user, involving the patient in setting his or her own goals.

Domain Model: Defines the aspects of the application that can be adapted or which are otherwise required for the operation of the adapted system.

Interaction Model: (i) Captures the appropriate raw data and records aspects of the individual user's observed behaviour. (ii) Represents the inferences that can be made, adaptations which the system can accomplish, and evaluations of the interaction which are possible.

Table 2. *A simple example of possible model values.*

User Model	Domain Model	Interaction Model
Range of movement	Course width	Outside gates missed $\Rightarrow$ narrow course if user path did not approach the outer limits of the course

The adaptive component of the system records initial user performance and updates task goals within a level on the basis of user performance across blocks of trials. The size of training blocks and the frequency of update depends upon the practice schedule and specific aims of the therapy programme. At this level some degree of supervisory input from the therapist is essential, to make executive decisions, regarding schedule of practice.

3.3 Schedule of practice

The primary goal of the system is to provide the capability for unsupervised practice of simple movements at the appropriate level. There is the need for supervisor decisions on the intensity/duration of practice, task variation and type of feedback:

Current research generally supports the role of fixed repetitive movements, with high frequency feedback during the initial stages of movement (re-)acquisition. There is strong evidence, however, that variable practice is necessary to ensure generalisation of the skill outside of the specific conditions of practice. A reduction in the frequency and specificity of feedback can also increase retention and learning. There is a transition to be made from providing the patient with a simple stable task, where errors are explicitly flagged, to one where the parameters vary within their achievable range across trials, and feedback is less specific to encourage patients to recognise their own errors. The decision regarding the type of practice that is most suitable for a particular patient requires clinical judgement.

Given that the system is in its pilot stage it is also wise to defer the decision regarding the level that a patient should attempt or when a patient should switch levels. The system can provide support for these decisions by providing data regarding: speed, accuracy, and smoothness of movement at each level or practice block. There are two correlated sets of data, user movements and the resulting change within the environment.

4. SUMMARY

We have described a system for the practice of simple movement patterns that should form the building blocks of more complex functional skills. The twin aims were to provide a simple, but motivating, environment for the repetitive practice of motor skills, while at the same time allowing generalisation to a wide range of motor tasks. By structuring a simple set of virtual environment parameters (e.g. the slalom task levels) there are few system constraints on the input movements. The input device used will dictate the interaction between the patient and the application. The same task may be performed with various input devices, dependent upon the patient's abilities and needs. For our trials we have deliberately chosen a manual control task and postural control (weight shifting) task, to pilot the system across the fine-motor, gross-motor dichotomy. A significant problem in this field is that relatively few developments in the academic sector make the transition to rehabilitation units. One of the primary issues is equipment cost and the cost of support. In the UK we are still some way from a 'wired retired society', but the percentage of the retired population with computer and internet access will increase in the next 10 years. This raises the potential for home-based therapy, in a number of areas, where therapists can check practice schedule and performance via remote links. A stumbling block in this scheme is that rehabilitation systems have been viewed as a relatively small commercial market. Hence although there is a wide range of games and fitness aids that allow web-interaction with others, there is relatively little that can be adapted specifically to rehabilitation. In this respect we believe that rehabilitation systems should capitalise upon the advances in games systems rather than try to swim against these trends. By focusing on using DirectX libraries, with standard acceleration, and adaptations of low-cost games (USB) devices we hope to develop a system that is, in principle, portable to any home/hospital PC with reasonable graphics performance.

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