Robot aided therapy: challenges ahead for upper limb stroke rehabilitation

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ABSTRACT

People who have been discharged from hospital following a stroke still have a potential to continue their recovery by doing therapy at home. Unfortunately it is difficult to exercise a stroke affected arm correctly and many people simply resort to using their good arm for most activities. This strategy makes many tasks difficult and any tasks requiring two hands become nearly impossible. The use of haptic interface technologies will allow the reach and grasp movements to be retrained by either assisting movement, or directing movement towards a specified target. This paper demonstrates how initial work on machine mediated therapies can be made available to a person recovering at home.

1. INTRODUCTION

Stroke is a leading cause of disability in the UK, with incidence rates between 1.25 and 1.8 per 1000 people per annum with the rate higher in Scotland and higher for men (Stewart et al, 1999; Scottish Health Statistics, 2002). Traditional treatments rely on the use of physiotherapy that is partially based on theories and also heavily reliant on the therapists training and past experience. The lack of evidence to prove that one treatment is more effective than any other makes the rehabilitation of stroke patients a difficult task. Upper limb motor re-learning and recovery levels improve with intensive physiotherapy. The need for conclusive evidence supporting one method over the other and the need to stimulate the stroke patient clearly suggest that traditional methods lack high motivational content, as well as objective standardised analytical methods for evaluating a patient's performance and assessment of therapy effectiveness. Although the causes of stroke are well known and it is possible to reduce these risks, there is still a need to improve rehabilitation techniques.

2. CURRENT STATE-OF-THE-ART

2.1 Early interventions

According to physiotherapy literature, attention and motivation are key factors for motor relearning following stroke (Yekutiel, 2000). One way to achieve early intensive interventions is via machine mediated therapies but there is a lack of good tools available to the therapist.

Several authors have already proposed the use of robotics for the delivery of this type of physiotherapy. The first far-reaching study on acceptance of robot technology in occupational therapy for both patients and therapists was done by Dijkers and colleagues using a simple therapy robot (Dijkers et al, 1991). Dijkers study reports a wide acceptance from both groups, together with a large number of valuable suggestions for improvements. Advantages of Dijkers therapy include the availability of the robot to successively repeat movements without grievance, as well as, the ability to record movements. However, there was no measure of movement quality and patient cooperation was not monitored.

2.2 Recent research

More recent studies however, follow a more task oriented approach. Johnson et al, (1999) have developed the SEAT: "simulation environment for arm therapy" to test the principle of the 'mirrored-image' by the provision of bimanual, patient controlled therapeutic exercise. The device comprises of a customised design of a car steering wheel equipped with sensors to measure the forces applied by patient's limbs, and an electrical motor to provide pre-programmed assistance and resistance torques to the wheel. Visual cues where given to the patient via a PC-based driving simulator that provided graphical road scenes. The interface allowed the participation of the patient in the task and the involvement of the paretic limbs in the exercise (Johnson et al, 2003).

Based on the same mirror image concept, Lum and colleagues (Lum et al, 1999) at VA Palo Alto research introduced the MIME: "Mirror-image motion enabler". The initial MIME prototype used a Puma-260 robot coupled through a force and torque transducer to one of the forearm splints used to support the patients arms weigh. The splints were free to rotate and tilt at the end of modified mobile arm supports. In the current MIME workstation, the robot is a Puma-560, the paretic limb mobile arm support is eliminated, and a 6DOF position digitiser replaces the contra-lateral support. The Puma-560 facilitates unilateral therapeutic exercises in 3 modes and 12 trajectories. A computer controls movement of the robot, with specific pre-programmed tasks tailored to the subject's level of recovery and therapeutic goals. Clinical trials with 27 chronic stroke patients (> 6 months post stroke) based on Fugl-Meyer exam, have shown that low compliance systems do not influence negatively the upper limb joint passive range of motion and pain. Results also suggested that robot-aided therapies are safe and effective for neuro development treatment (Shor et al, 2001). This work is now being commercialised by Dr. Mahoney at Applied Resources, USA.

Work done at MIT by Krebs et al, (1999) on the development of a new robot that allowed the patient to exercise against therapist nominated stiffness and damping parameters uses a different approach from the systems described so far and is the project with more exposure to patients in the literature to date. Their MIT-MANUS a 3DOF (2DOF active 1DOF passive) planar manipulator, has performed a series of clinical trials since 1995 at Burke Rehabilitation Hospital. Recent results were reported (Krebs et al, 2001) from a total of 76 patients assessed for upper limb subsection of the Fugl-Meyer test, motor power for shoulder and elbow, motor status score for shoulder and elbow, and motor status score for wrist and fingers. It was shown that the manipulation of the impaired limb influences recovery, the improved outcome was sustained after 3 years, the neuro-recovery process continued beyond the commonly accepted 3 months post-stroke interval, and the neuro-recovery was dependent on the lesion location. The MIT-MANUS mechanism however limits the range of possible therapies, has limited data collection facilities and does not allow bimanual therapies as the SEAT and MIME systems.

2.3 Gentle/s project

Gentle/s was a three year project funded by the European Commission to develop machine mediated therapies for neurorehabilitation of people with stroke. This project resulted in 3 prototype machines (Harwin et al, 2001). Gentle/s had the goal to both improve quality of treatment and reduce costs. A pilot study showed that subjects were motivated to exercise for longer periods of time when using a mixture of haptic and virtual reality systems (Loureiro et al, 2003).

Subjects used the Gentle/s prototype while seated at a table (figure 1). The person's arm was put in an elbow orthosis with wires suspending it from an overhead frame so as to eliminate the effects of gravity and address the problem of shoulder subluxation. Software was developed to manage the data collection, control and simulate complex virtual worlds (Loureiro et al, 2003). Subjects using the Gentle/s system could exercise "reach-and-grasp" type of movements (without the grasp component) in 3 degrees of freedom through interaction with a virtual room (figure 2 and 3). Task oriented activities can easily be created by a therapist using a graphical user interface and visual guidance is provided in the form of start/end points for a specific movement pattern. Control of human movement is based on minimum jerk theory and on a novel methodology that uses a spring and a damper combination that moves on a constrained path, called "bead pathway" (Amirabdollahian et al, 2002). The software also provides 3 different levels of movement control. The first called "patient passive mode" is aimed at users on the initial phases after the stroke, where the haptic device will teach the correct movements. The second, called "active-assisted mode" helps the user to complete a determined movement. The third mode, "active mode" provides only correction of movement. Clinical trials (Amirabdollahian et al, 2003; Coote et al, 2003) were conducted at Trinity College, Dublin and at Battle Hospital, Reading (total of 30 patients) and show the system was effective in improving recovery and acceptable to both subjects and therapists. The data from the principal study is in accordance with findings of the MIT MANUS studies (Krebs et al, 2001). One of the conclusions to take from the Gentle/S study is that this type of therapy appears to be particularly appropriate for more severely disabled patients. Further studies are needed to establish the level, nature, onset and determination of treatments that will result in the best recovery for an individual patient.

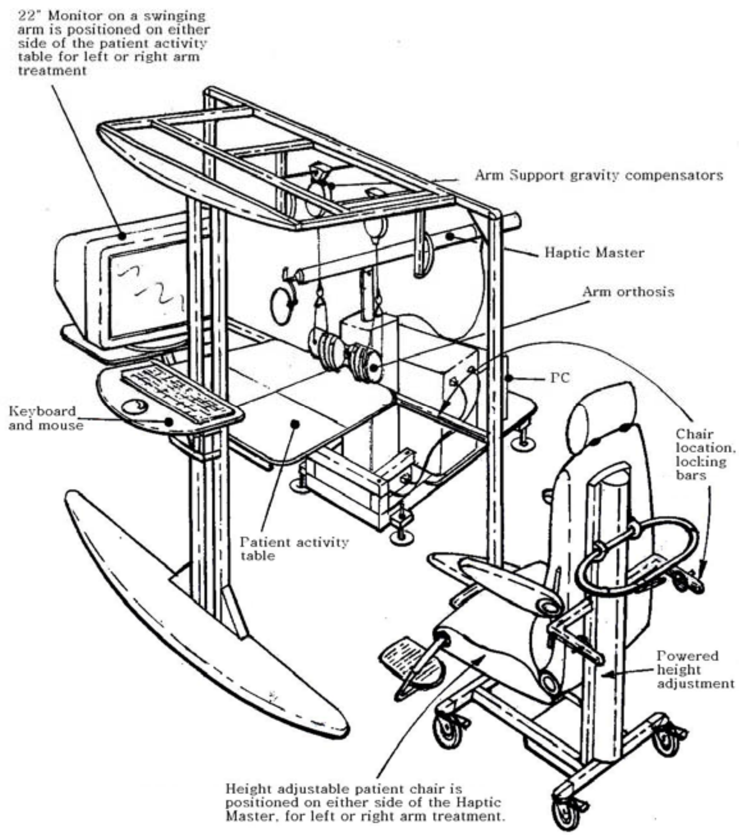

Figure 1. *The Gentle/s prototype system, showing the overall frame, an elbow orthosis suspended from the overhead frame, the HapticMaster with gimbals, the exercise table, computer screen and the wheelchair.*

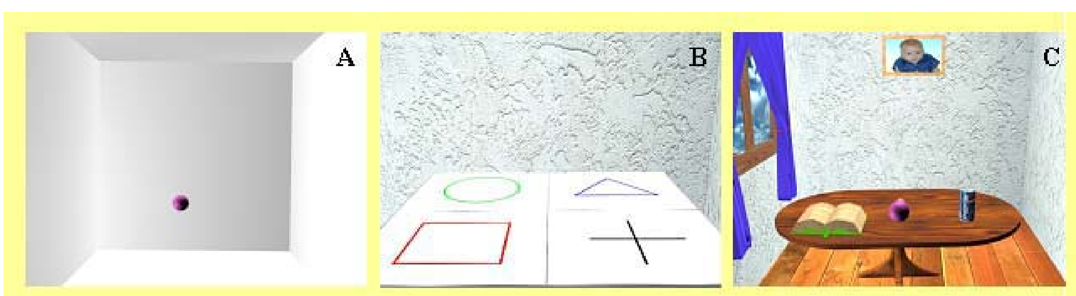

Figure 2. *Some of the virtual rooms available in the Gentle/s system. A) a simple environment that represents the haptic interface workspace and intends to provide early post-stroke subjects with awareness of physical space and movement; B) an environment that resembles what the patient sees on the table in the real world. This environment was developed to help discriminating the third dimension that is represented on the computer 2D screen; 3) A high detail 3D graphical environment of a room aimed at providing more motivational exercise activity.*

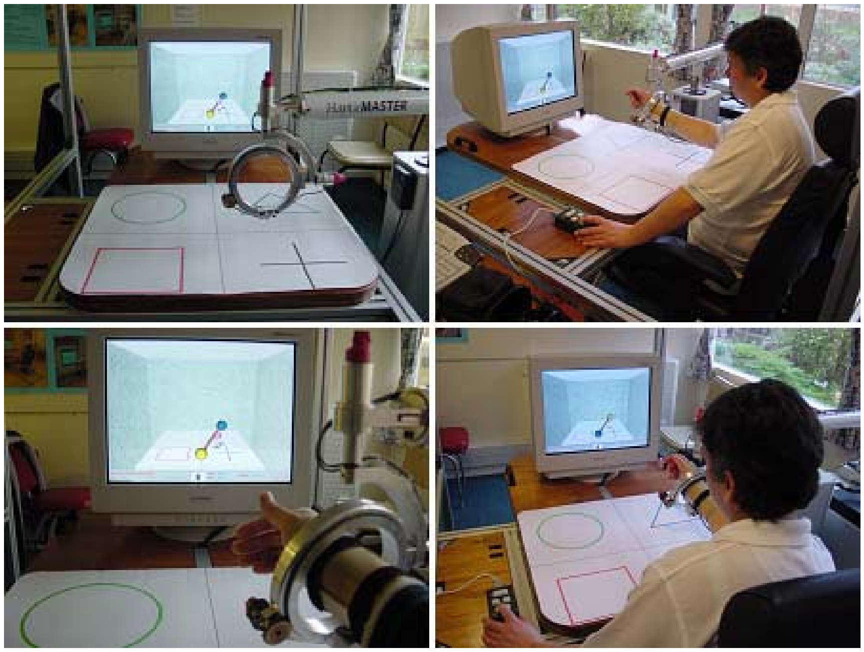

Figure 3. *Subject using the Gentle/s prototype system with one of the available virtual rooms. The virtual environment replicates the user's viewpoint in the real world where the mat with shapes is used to help perception of movement and space.*

3. THE CHALLENGE I: TECHNOLOGY NEEDED

The technologies presented on the previous section have the potential to revolutionise the way hospitals operate and hence, reduce the cost of stroke rehabilitation by allowing therapists and clinicians to manage a larger number of patients in the same amount of time. It is also likely that the recovery process can be reduced if this type of therapies is administrated at the correct intensity and method, at the acute phase of stroke. More clinical evaluation of current technologies is still needed to evaluate this type of approach, by increasing the number of subjects exposed to this type of therapies and to make the technology widely available, from its usage in hospitals to the patient's home. Gentle/s has identified the need of using the hand as well as the forearm and upper arm in the rehabilitation process of the upper limb using VR. Exposure of Gentle/s to the media (BBC, Discovery channel) generated a high level of interest in home based systems. This interest from people with a stroke, coupled with the results from the Gentle/s project, are a strong indication of a need for a high quality home therapy approach to stroke rehabilitation.

Reinkensmeyer has demonstrated home based rehabilitation using an adapted 'force feedback' games joystick (Reinkensmeyer et al, 2001). Therapies were downloaded from a web site and these could provide physically assist or resistance to movement as the user exercises. The exercises were quantified giving a level of feedback of performance, thus allowing users and their caregivers to assess rehabilitation progress. The study was small and suffered from the very small workspace and low level of force assistance provided by the joystick but it gives a good indication of the acceptability of this approach.

It is clear from our work in the Gentle/s project that there is a need to develop the technology in two areas. The relatively low levels of media exposure showed the need for a device that can be loaned to well motivated patients on leaving inpatient rehabilitation services. This device would be 'on loan' to the patient during possibly the 6 months following discharge and would provide challenging and motivating therapies to the individual, and at the same time, communicate with a central server to report usage, and update treatments. It is apparent that such a machine needs to have a relatively low cost, but more importantly needs to fit within the person's home environment so qualities such as light weight, small foot print and low power consumption will necessarily limit the abilities of the technology. In this regards the requirement of the Gentle/s technologies to enforce (albeit with varying levels of encouragement) a particular movement will probably need to be relaxed. A system based on guided weightless arm support is a better alternative as it can better meet the needs of a home based system. It may well be possible to use the person's non-affected hand to provide guidance by developing the ideas championed by Lum et al, (1999) in the MIME approach. It would be relatively straightforward to provide the car steering mechanism suggested by Johnson et al, (2003) as a home based system although this single application area may be too restrictive to promote reasonable recovery of motor movements in a large workspace.

The need for full functioning hospital systems remains, although considerably more work is needed to assess both the usage and the impact of this type of device in a hospital setting. There is a need for better assessment methods in stroke rehabilitation, separated from the intervention. Simplistic and subjective scores collected over a short time period are the norm for most assessments and these are insensitive to functional recovery. Furthermore, there is a strong need to move this type of treatment into the acute phase of stroke recovery, ideally beginning machine mediated therapies within a few days of admission. In many places this requires a hospital ward based machine that, although under the jurisdiction of the therapy staff, can be set up and run by the nursing staff as per the therapist's prescription for the patient (in the same way drugs are administered by nursing staff to the doctors prescription). This machine would need all the technical aspects of the Gentle/s system of having a reach commensurate with upper limb movement, requiring and encouraging patient involvement and giving goal directed therapies. It also should promote reach & grasp, manipulation and a combination of reach grasp and manipulation, in contrast to the Gentle/s prototype that only focused on reaching movements.

4. THE CHALLENGE II: QUESTIONS TO BE ANSWERED

Research on the area of rehabilitation robotics and recent results obtained with the Gentle/s system raised several research issues in the perspective of stroke, such as the need to be able to rehabilitate both reach and grasp in a context that allows the manipulation of objects in virtual tasks. It is not clear if recovery levels are attributed to the haptics alone or to a combination of visual and haptic cues, and performance cues need to be investigated further.

The hypothesis is that by giving individuals who are recovering from a first stroke access to motivating and challenging therapy 'on demand' and at their convenience at home, they will exercise for longer in a physiologically appropriate way that will lower their level of impairment and their disabilities. These therapies must be delivered in a structured environment that is well monitored so they are acceptable to the clinicians responsible for the management of the patient's recovery.

Arm movements are so common that we easily forget how complex they are. Even a simple movement like reaching for a can of soft drink requires fine-tuned muscle activation patterns. At present the authors are working with the aim to derive engineering based conclusions about stroke by the investigation of the effects of haptics and virtual environments in the rehabilitation process of the upper limb in stroke rehabilitation of the hand, from a systems point of view in order to identify better treatment alternatives.

The authors consider that better functional and motor recovery outcomes of stroke patients will be achieved where patients receive a repetitive, challenging and motivational machine mediated therapy that encourage reach and grasp movements. Part of our current and future work is devoted to the development of modular systems (arm support mechanisms, grasp assistance modules, arm reach movement assisting modules based on haptic interface technology, movement control software, data management, etc) that can be placed on a home context. Arm support mechanisms can be in the form of a forearm orthosis that can replicate the support mechanism developed for the Gentle/s project but instead of a large frame, it could be mounted on a chair. Grasp assistance modules could be in the form of a mechanism that can either simulate the force/position response of a grasp, or where the person has no discernable ability to move their fingers, move the fingers and thumb in a pattern that mimics the natural grasp of an object. As for arm reach movement assisting modules, these would assist with the reach phase of a reach and grasp movement. This can be either by constraining the person's arm to the 'correct' path, or if the person can not make the complete movement, the arm assistance module would move the persons arm along a nominally 'correct' path.

It is equally important to develop models of human control that are clinically useful and mechanically accurate. For example, if upper limb is subject to mechanical loading for a period of time, can we determine if the brain will over time adapt and adjust to added stiffness, mass and inertia? One can then postulate that stroke magnitude can be reduced if subjects are submitted to training in a context similar to the Gentle/s system. There is a need to understand stroke from a systems perspective, that is model the response to mechanical loading and hence develop better therapeutic and restorative methodologies. These and other questions are the source of our motivation to contribute to the development of the field of machine mediated neurorehabilitation to amass evidence on the clinical viability and the commercial potential of modular home based systems. Preliminary results on this area will be of interest to both clinical and commercial players in this field and will enable the larger studies that are needed for bodies such as NICE (National Institute for

Clinical Excellence). The long term purpose is to introduce revolutionary thinking into the traditionally under-regarded field of rehabilitation.

Our drive is also reflected on the challenges of reducing the current costs of systems such as Gentle/s that can be used at home and focusing on the rehabilitation of the entire upper limb. This includes the need to investigate; 1) real and virtual grasp exercises with healthy subjects to aid the development of linear and parametric models characterising the dynamic properties of the hand, wrist and forearm of stroke victims. 2) user involvement for increased recovery levels and this is reproduced by the level of interaction and the feedback provided to the user. Such level of interaction in virtual tasks need to be enhanced by means of the addition of active hand orthoses (exoskeleton) to the current systems, which should allow for grasping, monitor and parameterisation of the hand for different types of grasping activities. Bearing in mind that, physiotherapy practice is not guided explicitly on theories or research on the literature but on the experience that therapists acquire by working with patients and other experts in the field (and obviously on the type of approach that they were trained on) it is paramount that assessment methods become more objective. Traditional physiotherapy assessment methods are inconsistent varying from one therapist to another and from hospital to hospital, consequently it is important that the new machine mediated therapies are able to provide useful objective measures of patients' performance that can be easily analysed by clinicians and therapists alike. Similarly, motivational techniques should be taken into consideration when developing activities based on virtual environments and therapy performance cues in the form of encouraging feedback (sounds, visual stimulation, and task completion reward schemes) should be provided to the user.

5. CONCLUSIONS

In the first part of this paper we present the current state-of-the-art on machine mediated therapies for upper limb stroke rehabilitation, where a review of past/present research studies in this area is discussed and the Gentle/s prototype placed in perspective within the available technology.

The second part concentrates on our research commitments and on our views of what lies ahead. Our motivation is towards innovative robotic technology that could be placed into a home package to allow patients with upper limb weakness due to stroke, to practice meaningful interactive exercises in a virtual environment, with robotic delivered feedback and guidance. We have already shown that machine mediated therapies (MMT) can be delivered in the hospital environment to stroke patients with upper limb weakness with no harmful side effects and with positive results for some individual patients. Similarly, this work has been replicated elsewhere.

There is now a need to test whether machine mediated therapies can be effectively delivered in a home environment, thus benefiting from the cosy, relaxed home environment to reduce impairment and disability, and therefore reducing the rehabilitation associated costs. Low cost modular home based systems, can also provide patients with the opportunity to work as hard as they want to on a particular disability. This approach will also allow the patient the opportunity to demonstrate initiative and independence in their individualised home-based rehabilitation programme.

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6. REFERENCES

DJ Reinkensmeyer, CT Pang, JA Nessler, and CC Painter (2001), Java therapy: web-based robotic rehabilitation *Proc. Int. Conf. Rehab. Robotics, Integration of Assistive Technology in the Information Age,* M. Mokhtari (Ed.), IOS Press, pp.66-71.

F Amirabdollahian, R. Loureiro, and W. Harwin (2002), Minimum Jerk Trajectory Control for Rehabilitation and Haptic Applications, *Proc. IEEE Intl Conf. on Robotics & Automation,* Washington, DC, pp.3380-3385.

F Amirabdollahian, E. Gradwell, R. Loureiro, C. Collin, and W. Harwin (2003), Effects of the Gentle/s Robot Mediated Therapy on the Outcome of Upper Limb Rehabilitation Post-Stroke: Analysis of the Battle Hospital Data. *Proc. of 8th International Conference on Rehabilitation Robotics,* Published by HWRS-ERC Human-friendly Welfare Robot System Engineering Research Center KAIST, Republic of Korea, pp.55-58.

HI Krebs, N Hogan, N., BT Volpe, ML Aisen, L Edelstein, and C Diels (1999), Robot-Aided neuro-Rehabilitation in Stroke: Three-Year Follow-up, *IEEE Intl. Conf. Rehabilitation Robotics,* Stanford, CA, USA.

HI Krebs, BT Volpe, J Palazzolo, B Rohrer, M Ferraro, S Fasoli, L Edelstein, and N Hogan (2001), Robot-aided neuro-rehabilitation in stroke: interim results on the follow-up of 76 patients and on movement performance indices, *Proc. Int. Conf. Rehabilitation Robotics, Integration of Assistive Technology in the Information Age,* Mounir Mokhtari (Ed.), IOS Press, 9, pp. 45-59.

JA Stewart, R Dundas, RS Howard, AG Rudd and CDA Wolfe (1999), Ethnic differences in incidence of stroke: prospective study with stroke register, *British Medical Journal (BMJ),* 318*, pp. 967 – 971.*

M Yekutiel (2000), *Sensory re-education of the hand after stroke,* Whurr Publishers, London.

MP Dijkers, PC deBear, RF, Erlandson, K Kristy, DM Geer, and A Nichols (1991), Patient and staff acceptance of robot technology in occupational therapy: a pilot study, *Journal of Rehabilitation Research and Development,* 28, *2*, *pp. 33-44.*

MJ Johnson, HFM Van der Loos, CG Burgar, and LJ Leifer (1999), Driver's SEAT: simulation environment for arm therapy, *Proc. IEEE Intl. Conf. Rehabilitation Robotics,* Stanford, CA, USA, pp. 227-234.

MJ Johnson, HFM Van der Loos, CG Burgar, PC Shor and LJ Leifer (2003), Design and evaluation of Driver's SEAT: A car steering simulation environment for upper limb stroke therapy, *Robotica,* **21,** *pp.13-23.*

PC Shor, PS Lum, CG Burgar, HFM Van der Loos, M Majmundar, and R Yap (2001), The effect of robotic-aided therapy on upper extre,ity joint passive range of motion pain, *Proc. Int. Conf. Rehabilitation Robotics, Integration of Assistive Technology in the Information Age,* Mounir Mokhtari (Ed.), IOS Press, 9, pp. 79-83.

PS Lum, CG Burgar, DE Kenney, and HFM Van der Loos (1999), Quantification of force abnormalities during passive and active-assisted upper-limb reaching movements in post-stroke hemiparesis, *IEEE Transactions on Biomedical Engineering,* 46, *6, pp. 652-662.*

R Loureiro, F. Amirabdollahian, M. Topping, B. Driessen, and W. Harwin (2003), Upper Limb Mediated Stroke Therapy - GENTLE/s Approach, *Special Issue on Rehabilitation Robotics Journal of Autonomous Robots*, Kluwer Academic Publishers, 15, *1, pp. 35-51 (ISSN 0929-5593).*

Scottish Health Statistics (2002), *ISD Scotland National statistics release,* web resource: http://www.isdscotland.org/isd/info3.jsp?pContentID=2857&p_applic=CCC&p_service=Content.show& *(Accessed on 14-07-04)*

S Coote, EK Stokes, BT Murphy, WS Harwin (2003), The effect of GENTLE/s robot mediated therapy on upper extremity function post stroke, *Proc. of 8th International Conference on Rehabilitation Robotics,* Published by HWRS-ERC Human-friendly Welfare Robot System Engineering Research Center KAIST, Republic of Korea, pp.59-61.

W. Harwin, R. Loureiro, F. Amirabdollahian, M. Taylor, G. Johnson, E. Stokes, S. Coote, M. Topping, C. Collin, S. Tamparis, J. Kontoulis, M.Munih, P. Hawkins, and B. Driessen (2001), The Gentle/s project: a new method for delivering neurorehabilitation, *Assistive technology - added value to the quality of life AAATE'01,* IOS Press Amsterdam C. Marincek et al. pp.36-41.