Challenges and opportunities for robot mediated neurorehabilitation

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***Abstract*— Robot mediated neurorehabilitation is a rapidly advancing field that seeks to use advances in robotics, virtual realities and haptic interfaces, coupled with theories in neuroscience and rehabilitation to define new methods for treating neurological injuries such as stroke, spinal cord injury and traumatic brain injury. The field is nascent and much work is needed to identify efficient hardware, software and control system designs alongside the most effective methods for delivering treatment in home and hospital settings. This paper identifies the need for robots in neurorehabilitation and identifies important goals that will allow this field to advance.**

I. Introduction

The use of robots for providing physiotherapy is a relatively new discipline within the area of medical robotics. It emerged from the idea of using robots to assist people with disabilities. For example, the Rancho Golden, developed in 1969, was a powered orthosis with six degrees of freedom to assist movements of individuals with polio [1]. The transition to using robots to assist a therapist with a rehabilitation exercise was identified by several groups although Erlandson was possibly the first to publish a working implementation [2]. The adaption of the idea to robotic devices to assist in neurorehabilitation was first identified by Nevile Hogan at MIT [3] and is in the area of neurorehabilitation where there is currently a high rate of expansion in the field. This rapid growth can be attributed to several factors, the first being the emergence of hardware for haptics and advanced robotics that could be made to operate safely within the human's workspace. The dramatic drop in the cost of computing along with the emergence of software to support real-time control further helps to reduce the costs of producing research prototypes and commercial products. This technological shift has coupled with better knowledge of the rehabilitation process and the social need to provide high quality treatment for an ageing population.

The focus of this paper is on robotic assistance in neurorehabilitation. Although this usually means stroke rehabilitation many of the arguments put forward are also appropriate for people with traumatic brain injury, spinal cord injury and other damage that might occur to the brain or spinal cord. Thus these areas are included in our discussions. Likewise the term 'robot', which can be seen as pejorative by practitioners if incorrectly introduced, is considered interchangeably with the concept of a haptic interface. The only difference is that the latter is a more specific term relating to a robot used to guide or restrict the movements of a person who is in direct contact with the robot end effector. In most cases the robot or haptic interface is not used in isolation and requires at least a computer interface and possibly also a virtual environment to establish the particular therapy.

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II. Importance of the problem of stroke

Cerebral vascular accidents, more commonly referred to as strokes, are an important problem in clinical medicine. They are a leading cause of disability within the developed world.

A stroke is the consequence of cell death within the brain relating to either internal bleeding or a blockage in one of the two main supplying arteries. The term 'ischemic stroke' accounts for 80% of cases and refers to the condition where an artery becomes blocked by an embolism or thrombosis, whereas 'hemorrhagic stroke' accounts for the remaining 20% and is caused by blood leaking into the brain. The consequence of either etiology is cell death that results in a loss of brain function. Conditions such as brain tumours or traumatic brain injuries may have similar consequences to those of a stroke. These consequences include hemiplegia (on the side opposite to the injury), visual neglect, cognitive difficulties (relating to thinking, learning, concentrating and decision making), and speech and language difficulties including dysarthria and aphasia. Although technology may contribute in other areas of neurorehabilitation this article will concentrate on the rehabilitation of movement disabilities.

Stroke statistics are available for the developed world. The rate is highest for men in Finland (2.9 per 1000) and in Japan (2.8 per 1000) [4]. In the UK the rate is between 1.25 and 1.6 per 1000. Incident rates in Germany and France are broadly similar to the UK [5]. In affluent areas of the USA the rate can be as low as 0.9 per 1000 [6].

Stroke is the third leading cause of death and the leading cause of severe disabilities in the developed world. The current assumptions are that about 3/4 of people who have had a stroke will survive for at least a year, but around 1/3 of survivors will have moderate to severe disabilities relating to movement, speech, concentration and cognition [7].

Age is a strong factor in stroke with 88% of individuals who have had a stroke being over the age of 65. Indeed beyond age 55, the likelihood of stroke doubles for every ten additional years of age. Other factors that deleteriously affect the risk of stroke include ethnicity, poor diet, tobacco usage, use of anticoagulant drugs, a previous stroke or prior transient ischemic attack (TIA, also known as a ministroke).

So it is clear that stroke is a concern for our society, especially given the demographics of a growing population of elderly people and by implication more people who are at risk of a stroke. In the USA the number of people over the age of 60 years will increase by 10 million (22%) over the next 10 years. Another pressure comes from the fact that survival rates from stroke are increasing due to the improvement in acute medical care. The cost of hospitalisation of stroke also helps to make the case for robot assistance in neurorehabilitation of people following a stroke. The costs to the UK National Health Service of stroke are estimated to be over £2.3 billion per year and the cost is expected to rise in real terms by around 30% by the year 2030 [8]. Similar economic pressures prevail in the USA where there is an annual spending of $30 billion on physical rehabilitation.

III. Background and Theory of Neurorehabilitation

A. Theoretical background to neural control of movement

Observations on repetitive cyclic movements in lower limb studies show that there is some variation in the neuromechanical properties of each step, i.e. movement variability is a normal feature of the neural control strategy of the nervous system.

Similarly animal studies based on a transection of the spinal cord show that the spinal cord can learn a motor task, in particular the rhythmic locomotion activities while bearing full body weight [9]. This is evidently a learnt skill as it is only acquired when the animal is given treadmill training. It thus seems logical to assume that the spinal cord as well as the brain has a role in movement.

For lower limb movement it is hypothesised that repetitive training increases the efficacy of a more selective group of synapses and circuits, which will reduce the variance and increase the probability of success in generating consecutive successful steps. The persistence of these changed probabilities reflecting improved synaptic efficacy in a more selected network of neurons seems to have multiple time courses, suggesting multiple mechanisms of learning and memory.

The situation in intentional movements typical of the upper limbs is more complex. It is clear that movement targets are acquired from a variety of sensory channels including vision and touch and information from these sensory channels is used to update internal models. These models not only encode the state of the world, but also the sensory consequences of any interactions. A decision to make a movement registers in the premotor cortex up to 250ms before activity in the motor cortex [10], and it is hypothesised that an internal model is being prepared to predict the consequences of the movement [11].

Strokes that are linked to a movement impairment are usually due to thrombosis or aneurysm in the mid cerebral artery located near the sensory-motor cortex. This explains high involvement of motor disabilities following a stroke. Given the complexity of the movement process and the severity of the stroke it is evident that movement can be impaired at multiple levels, with a result that the rehabilitation process does not follow a clear path of recovery.

B. Theoretical background on neuroplasticity

A key concept that underpins all forms of neurologically directed physiotherapy is that of brain plasticity. Evidence from fMRI and transcranial magnetic stimulation (TMS) [12], [13] has shown that the visual cortex of people who are blind, is reorganised to process somasensory and tactile information such as reading and interpreting Braille. This conclusion is also confirmed by animal experiments [14] and shows that the transfer of activity is both intra and inter modality, and that where there is a need for the brain to reorganise to adapt to new circumstances this reorganisation is not necessarily confined to the understood maps of the Homunculus brain [15]. The fact that this reorganisation occurs even in mature adult humans is a primary justification for neurorehabilitation following a stroke.

The mechanisms for this reorganisation are still uncertain although there is a body of evidence of some interesting effects associated with learning and memory. Among these is histological evidence that an increase in neuron activity leads to modifications of the number of synaptic connections and a greater level of dendritic branching. Also effects such as long term potentiation (LTP) following neuron activity can be observed. This is the phenomenon whereby a neuronal cell becomes hyper-sensitive when there has been a recent history of firings and this increase in sensitivity can last several weeks. Although there is no objective evidence it is suggested that encouraging LTP with an enriched environment might be a basis for neurorehabilitation [16].

A stroke causes neuron death to a focal area of neurons. Surrounding this area is an ischemic penumbra where the neurons are no longer functioning normally due to the lack of blood supplying both oxygen and ATP to the neuron. It is in this penumbra where the recovery of function is most likely to occur and the evidence is that because the blood supply has not returned to normal these penumbra neurons die and the clinical deficit that was observed just after the incident becomes fixed [17].

IV. Robotics and Virtual reality in rehabilitation

Evidence for integrating stroke care to include early and appropriate rehabilitation is the reduction in mortality of about 20% and the reduction of mortality and severe disability by 30% [18].

A key challenge is how best to enhance the therapist's skills with robot technology. An appropriate concept is to consider the robot as an advanced tool under the therapist's direction. As such the robot can best handle relatively simple therapies that are characterised by a repetitive and labour intensive nature. Clinical decisions should be managed by the therapist and, when appropriate, planned and executed on the robot. This approach would be part of an integrated set of tools that would include simpler, non robotic approaches such as intelligent sensing of therapy tools that could keep the therapist and patient informed about the progress of an individual exercise as well as the overall treatment. There is already a precedent for such tools in intensive care nursing where staff use a range of highly complex tools to monitor and deliver care to their patients.

A. Technologies for neurorehabilitation

When a robotic device is coupled with a three-dimensional graphic display such as shown in figure 1 the sensorimotor system is able to engage all normal types of visual and motor adaptation. The robotic actuator is typically a specially designed robot or a haptic interface, which while easily moved by the user, may also resist or apply forces. This process appeals directly to the person's proprioception (position and velocity of the limb) and to the sense of touch. Commercially available robotic devices are now available that provide haptic interaction with humans. These devices include the PHANToM (SensAble Technologies, USA), the HapticMaster (FCS robotics, The Netherlands) and the WAM arm (Barrett Technologies, USA). The addition of a graphic displays that uses Virtual Reality (VR), enhances the sense of the interaction. Although stereoscopic vision (for example with shutter glasses) and head tracking may enhance the sense of realism of the interaction, the acceptance by the subjects along with the value to the neurorehabilitation process is relatively untested.

These haptic and graphic virtual environments offer several advantages. Properties of objects can be changed in an instant with no setup and breakdown time. This element of surprise is critical for studying how the sensorimotor system reacts and adapts to new situations. For rehabilitation, friction or mass can be suppressed, or mass can be separated from weight and the weight reduced during the early stages of recovery.

B. Upper limb rehabilitation methods

Work by Hogan and Krebs on the design of a 2-link robot, MIT-MANUS, along with its evaluation on a cohort of subjects recovering from stroke was the first to make a major impact on upper limb neurorehabilitation [19]. MIT-MANUS is a high quality manipulandum that works in the horizontal plane. However it is evident that more degrees of freedom should be available to allow movement of the upper limbs against gravity.

Burgar et al. investigated bimanual motion using a six degree of freedom PUMA560 robot plus additional force/torque sensor linking the robot to the subject [20]. This work prototyped several possible therapy modes including a mode known as MIME (Mirror image motion enabler) whereby movements of the stroke affected arm could be patterned to follow the motion of the persons unaffected arm. Johnson used this principle along with a realisation that a strong stimulus for motivation was to regain the ability to drive, to develop 'Drivers SEAT' [21]. A modified steering wheel helps the stroke affected arm in preference to the unaffected arm by measuring the relative force contributions from each. The principle was integrated into a simulation of driving to encourage both motor relearning and relearning of driving skills, thus providing a stimulating interactive environment.

Work by Reinkensmeyer [22] tested the potential of integrating the therapy with the measurement. This work looked specifically at factors affecting reach and attempted to extending the reaching movement with a one degree of freedom device.

An European project titled Gentle/s extended on the therapies offered by the MIME system by offering the subject a choice of movement targets that were selected on the initiation of a particular movement [23]. The Gentle/s work also patterned movements to follow stereotypical movement patterns [24], as well as using an arm deweighting mechanism similar to those used in lower limb rehabilitation.

The hardware for upper limb therapy prototypes has tended to separate reach and grasp as two separate activities. This is primarily due to engineering decisions. Thus, for example, the Gentle/s project dropped plans for retraining grasp so that it could focus on arm pronation-supernation [23]. This decision lead to the pre-commercial Gentle/s prototype shown in figure 2. This is still primarily the case although several groups are now investigating integration of reach and grasp into a single device.

A variety of control methods are being developed but all share the concept of guiding the stroke affected movement to achieve a target or tracking path. The algorithms are highly varied, and range from implementing virtual mass-spring-dampers and guiding the equilibrium point [24], to constraining movements to occur within a prescribed volume and changing the dimensions of the volume depending on the subject's success and abilities [25].

C. Lower limb rehabilitation methods

A technique known as partial body weight support usually forms the basis for lower limb neurorehabilitation [26], [27]. Although not necessarily robotic it simplifies many aspects of introducing robot mediated neurorehabilitation for the lower limbs. Partial body weight support usually requires that the patient wear a parachute type harness that is connected to an overhead gantry that allows the therapy to happen with only a percentage of the person's true weight appearing as a force on the treadmill.

Data collected by Visintin et al. [27] showed that after six weeks of exposure to partial body weight support therapy 4 times a week, subjects with stroke performed better in their ability to balance, in their motor recovery, in their ability to walk and in their endurance of walking.

The disadvantage of partial body weight support is that it requires greater involvement of the therapist, often requiring between two and three therapists are required to assist with the movement of the feet. Since these are repetitive and physically demanding tasks for the therapists it is an opportunity to introduce robotic based solutions. The potential for valuable robotic assistance is further enhanced when considering the safety of the patient in a partial body weight support mechanism and the fact that an inexpert therapist may be applying greater forces and giving fewer opportunities for the task to be completed unaided [28].

The robotic device must be able to guide the kinematics of the limbs during load bearing stepping to generate the afferent patterns that normally occur, and which in turn drive the spinal networks which generate the motor pattern. It appears that the control system needs to have some learning capability. It must be designed so that it can assist on an "as needed" basis, much like highly skilled physical therapists perform when teaching a spinal cord injured patient to relearn to walk. It is already apparent that complete, and stereologically constant assistance reduces the level of activation of the motor circuits that generate stepping. This apparent habituation and reduction in activity is not consistent with allowing these neural circuits to relearn. When exposed to a constant and invariant movement strategy, the neural control circuitry accommodates by becoming non-responsive to the imposed motion.

Colombo et al. [29] have presented some supportive evidence for gait retraining in severe brain injury. Using an alternative arrangement to partial body weight support this work is based on an inclined table with an integrated robotic stepping mechanism that moves the feet in a gait like cycle. The case study presented relates to a person with traumatic brain injury who was still unresponsive 14 months after injury. The subject received stepping retraining on inclined table treatment for five 20 minute sessions for three weeks.

The results showed significant improvement of the muscle tone between baseline and end of the 3 week training as well as an improvement of alertness, head position control and reaction to pain. The authors also noted better communication with the patient and better posture when seated in a wheelchair.

In recognition of the benefits of robotic based lower limb therapies several prototypes and commercial devices have emerged that provide robot step assistance.

These include PAM (Pelvic Assist Manipulator) and POGO (Pneumatically Operated Gait Orthosis), pneumatic robots that compliantly assist in gait training shown in figure 3. PAM can assist in five degrees of freedom of pelvic motion, while POGO can assist in hip and knee flexion/extension [30]. The devices can be used in a backdriveable mode to record a desired stepping pattern that is manually specified by human trainers, then replay the pattern with compliant assistance. During compliant replay, the devices automatically synchronize the timing of the replayed motions to the inherent variations in the patient's step timing, thereby maintaining an appropriate phase relationship with the patient. In spinal cord injuries the robot assisted stepping assistance must occur bilaterally, whereas for strokes it is most likely to be needed unilaterally. Similar commercial devices also exist such as the

Lokomat (Hocoma AG, Switzerland) where similar bilateral robotic elements are used to assist movement of the subject's leg while providing partial body weight support via a harness.

As in work on upper limbs the idea is to reduce the dependence on the robotic mechanism as far as possible to encourage motor relearning by the patient. One possible control mechanism is to define a target trajectory gait and then subject the limb to a force or torque field to return it to this trajectory only when the limb state is outside a prescribed boundary [31]. When compared to upper limb retraining, gait retraining has more repeatable cyclic operations which favours simpler control concepts. In contrast the engineering of lower limb rehabilitation devices needs to be more considerate of the dynamics of gait, and the forces applied to the legs and feet need to be larger although this engineering problem is simplified by using the partial body weight support mechanisms.

D. Perturbation methods

One important advantage of virtual systems is that they can distort reality. One study used altered visual feedback to ‘trick’ the nervous system into perceiving higher stiffness than was actually presented [32] Another tricked the nervous system to increase strength [33]. Still another used prisms that shifted the visual field to the right to cause adaptation in stroke survivors with hemispatial neglect, triggering the recovery process [34]. Clearly there is an advantage to such distortions of reality. Preliminary results point to a single unifying theory suggesting that errors induce movement adaptation, and judicious manipulation of error can lead to lasting desired changes.

Some preliminary studies show that stroke survivors respond to error augmentation [35]. In this study, stroke survivors experienced training forces that either amplified or reduced their hand path errors. Significant trajectory improvements occurred only when the training forces magnified the original errors, and not when the training forces reduced the errors or were absent. Hence causing adaptation by using error-augmentation training may be an effective way to promote functional motor recovery for brain injured individuals.

Other studies confirm the hypothesis that error augmentation leads to enhanced learning. Subjects learning how to counteract a force disturbance in a walking study increased their rate of learning by approximately 26% when a disturbance was transiently amplified [36]. In another study, artificially giving smaller feedback on force production has caused subjects to apply larger forces to compensate [37]. Several studies have shown how the nervous system can be *tricked* by giving altered sensory feedback [38], [32], [39], [40], [41].

Conversely, suppression of visual feedback may slow the adaptive process [42]. However, not all kinds of augmented feedback on practise conditions have proven to be therapeutically beneficial in stroke [43]. It may be that there are limits to the amount of error augmentation that is useful [44][45].

V. Measurements of success

A. Clinical measures

To get a new treatment accepted in practise requires evidence sufficient to convince the practitioner and the associated hospital management that the results will be effective. In the UK one arbiter of decisions to introduce new techniques is the National Institute for Health and Clinical Excellence (NICE). A recommendation about a new technology is based on a review of clinical and economic evidence, with a randomised controlled clinical study being the preferred instrument. A recommendation is based on the effectiveness of the intervention and the economic impact - ’does it represent value for money?’ The health economy in the USA is influenced both by government and private regulatory bodies, ranging from the Food and Drug Administration, and the Department of Veterans’ Affairs to individual insurance organisations.

These evidence based medicines require measurements with clinically accepted measures. A number of these exist that are relevant to the field of stroke rehabilitation (see http://www.strokecenter.org/trials/scales/) and these attempt to measure attributes such as consciousness, levels of pain, dexterity, mobility, spasticity, ability to perform daily tasks etc. Most clinical measures are based on subjective judgements, for example the Fugl-Meyer assessment is a widely accepted scale that attempts to measure motor function following a stroke [46]. However it is a general score and is based on rating attributes as 0-2 made by the clinician. Each attribute is then added together to produce either a subscales measure (for example motor recovery, balance, upper limb recovery, sensation, range of motion, sensation, pain) or a total score with a maximum of 124. The difficulty is then one of relating the recovery process to a subjective measure that is highly susceptible to noise. This is compounded by the relatively small numbers in any robotic based clinical study. A study in a drug trial with n= 500 is small, whereas a rehabilitation trial with n=50 is large simply because of the cost of acquiring the data [47]. Considerations for the design of a randomised controlled trial of a complex intervention such as rehabilitation are discussed in [47].

B. Robot based measures

Rehabilitation robots are atypical in that it is possible to use the same tool both to gather information for diagnosis, and be a part of the intervention. Experiments assessing movement often yield a large set of time-dependent multidimensional vectors which must be analysed. Intervention devices that allow us to measure the resulting position, velocity, and acceleration of the body with increasing precision lead to the question of how to evaluate performance or scrutinise error so that they answer a relevant question about neurophysiological function. In recent decades several studies have utilized robot technology in order to model the control exerted by the brain on upper extremity movement alone [48] [42] [49]. A number of hypotheses have been tested, such as: what are the relevant control variables (stiffness, force, position); how does the motor control system adapt to a novel environment (internal models, memory consolidation etc.); and how are multiple degrees of freedom controlled?

Examples of some common but non standardised measures of performance are: time to reach a target, the value number and time of occurrence of velocity peaks, the sum of jerk over the movement (the second derivative of velocity), the average or summed interface force with the robot [50]. With the variety of measures available, it is necessary to validate these for their ability to measure an underlying phenomena, the sensitivity to that phenomena, and the relevance of the phenomena to the recovery process.

In addition to the use of robotic devices for teaching or relearning as described above, they should be designed to have another feature, which will make them even more valuable. These devices should be able to provide ongoing feedback with respect to how much and what kind of work is being performed by the robot versus the subject. Theoretically, it is feasible for the human subject to monitor their level of performance throughout a given training session and over a period of weeks by simply observing a monitor which could easily demonstrate their degree of success e.g. their stepping. Thus, the robotic device, should have sensors to detect critical but yet undefined mechanical and perhaps physiological events, as well as having the capability of mechanically controlling the robot.

VI. Future prospects

A. Engineering challenges

The field of machine mediated neurorehabilitation has challenges both in engineering and clinical practise. On the engineering side of the equation there is a need for more integrated solutions. A discussion with interested therapists will quickly indicate that the range and complexity of movements that need to be coordinated, especially in upper limb work outstrips the practicalities of any of today's robots. Given that the therapy needs to be done in an environment that is safe for the patient and therapist, it is unlikely that any single hardware solution will be accepted. Therefore, realistically a number of robotic solutions will be required, ideally with similar protocols and interfaces so that the patient and therapist can transfer between machines without concern. Designing these solutions would also be simplified if it were clear what the best form of machine mediated therapies were. These answers will only come iteratively as machines are designed, tested clinically and the results published.

B. Novel measures

The measurement of success is highly unspecific if based on clinical measures alone, so along with this iterative design of therapies and machines must come realistic quantitative measurements of the underlying recovery process. There are some excellent opportunities for basing these measurement techniques on the current generation of robotic technology (including haptic interface and manipulandum technologies). It would seem that methods can be developed based on perturbing the limb either when stationary or during movement and using system identification techniques along with knowledge of the fundamental neural delays to identify intrinsic and reflex components as outlined in Kearney [51] and used extensively by Mirbagheri [52] and others.

C. Acute phase rehabilitation

Ideally machine mediated neurorehabilitation should be available to a person within a few days of the initial attack. When a person is in the acute phase of stroke they will be occupying a hospital bed so the initial equipment must be operable within that environment. Concerns such as access to the patient should they need emergency treatment such as cardiac resuscitation needs to be designed into a device that should be available to a possibly unresponsive patient. The equipment needed when the patient visits the rehabilitation gymnasium either as an inpatient or outpatient can necessarily be more specific for limbs and movements, and although not necessarily spacious, these areas are less constrained than the bed-side machines.

D. Home rehabilitation

Finally the concept of allowing the patient to continue rehabilitation at home is attractive to the patient who is keen to return to familiar surroundings, and economically sensible to the hospital who would like to increase through-put! But it is important that the patient is not abandoned at home with the equipment. Home rehabilitation is often self-directed with little professional feedback, and used so private insurers such as Medicare can encourage a reduced length of hospital stay and less therapy. Ironically, recent research strongly supports the delivery of more intensive therapy [53]. Techniques in telerehabilitation will need to be addressed to ensure that the machine mediated therapies are appropriate to the patient at their particular stage of recovery and so the equipment can be returned to a loan pool when the patient is no longer gaining benefit.

E. Funding

As with many nascent research areas there is a need for further funding [54] [55] if long term health cost savings are to be realised and the quality of life of the senior members of our society is to be improved. As a discipline the area is beginning to receive attention from commercial companies but it is an area where investment is conservative as companies are aware of the problems of translating research into product.

A pioneering company in the field of upper limb neurorehabilitation is Interactive Motion, USA. Their technology is based on the MIT-MANUS robot and has established systems in the USA, and the UK with an expectation of a greater mass of clinical evidence to follow. Several companies are investigating the market for lower limb rehabilitation again with the expectation of amassing greater clinical evidence on best clinical practise.

However public funding is still needed from governments and charities to advance the technology and to ensure independence of clinical results. This money is also needed to bridge the so called ’funding gap’ that occurs between the demonstration of a promising new technique and the acceptance of the technique by mainstream healthcare providers.

In the USA the National Institute for Disabilities and Rehabilitation Research (NIDRR) currently funds a rehabilitation engineering research centre on the topic, and project grants have been successfully funded by the National Institutes of Health and the Department of Veterans’ Affairs. In Europe, the European Commission has funded collaborative projects in the area and local governments have sponsored work at a lower level. However, it is a concern that the progress in the field may not be recognised by funding agencies at a critical

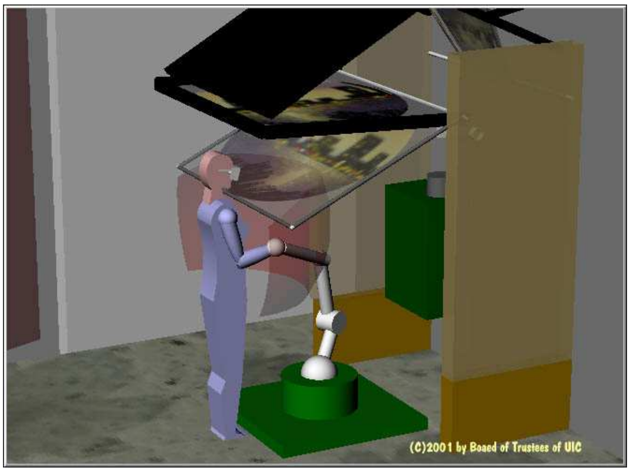

Fig. 1. Rehabilitation Institute of Chicago Virtual room (VRROOM) concept

point where more research and better collaboration should be fostered.

VII. Conclusions

In this paper we give a brief outline of machine mediated neurorehabilitation as an important emerging field in clinical medicine. We have highlighted some of the engineering problems and potential solutions that will result in effective treatments. One area for research emphasised in this paper is the challenge of measuring recovery in the patient when they are undergoing machine mediated therapies and we propose that perturbation methods can be used both to gain a better insight into the recovery process and also to improved the effectiveness of the treatment. The paper is highly focused on motor recovery in the upper and lower limbs but it should be remembered that the patient may have other stroke related impairments. Stroke rehabilitation is moving towards more integrated process and ideas in robotics and have much to offer in this scope.

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Fig. 2. Gentle/s commercial prototype for machine mediate neuro-rehabilitation

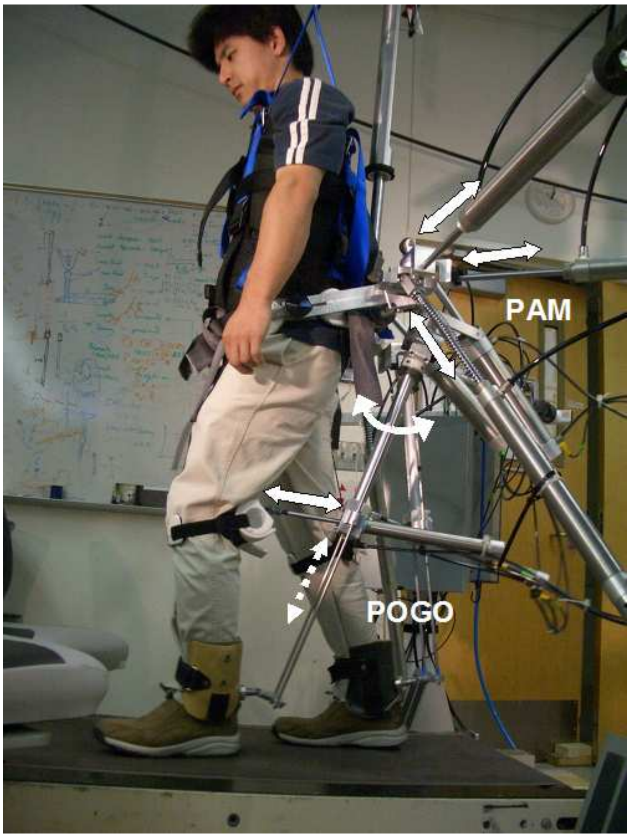

Fig. 3. PAM/POGO, two pneumatic robots used to assist gait retraining

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