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What should we consider when designing rehabilitation robots for the upper limb of the neurologically impaired?

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Abstract

Rehabilitation robotics has the potential to significantly increase access to useful therapeutic upper limb exercise for those suffering from neurological impairment. In order to maximise the potential of such technology to promote motor learning/relearning clearly we must consider carefully how it is designed, and who should be engaged in its development. In this paper we present our perspective on some important design considerations and highlight relevant literature. Our findings have implications for the development and optimisation of rehabilitation robotic technology for improving upper limb function in the neurologically impaired.

1 Introduction

Neurological impairment including stroke, the commonest form of adult disability in the USA, and cerebral palsy (CP), the commonest form of severe childhood disability in Europe (Hagberg and Hagberg, 1993), are a significant burden on healthcare providers with both conditions often affecting the volitional control of one or both upper limbs. Restorative technologies, such as rehabilitation robotics, aim to accelerate skill acquisition to increase the functional abilities of the neurologically impaired without device assistance. A benefit of rehabilitation robotics to healthcare providers is increased patient access to rehabilitation treatment as existing rehabilitation treatment is predominately delivered by therapy staff and as such is resource limited. Improved access to therapy maximises the potential of recovery and as a consequence a better quality of life whilst resulting in a more cost efficient healthcare provider.

The paradigm of upper limb rehabilitation robotics is a motivating computer environment, which promotes therapeutic movements of the impaired limb with a powered interface implementing a control algorithm to promote recovery. Rehabilitation robotic therapy for the upper limb has demonstrated statistically significant benefits, with improvements in kinematic parameters including movement time, path and smoothness of reach observed (Fasoli, et al., 2008, Huang and Krakauer, 2009, Fluet, et al., 2010, Weightman, et al., 2011, Norouzi-Gheidari, et al., 2012, Chen and Howard, 2014).

Rehabilitation robotics have demonstrated potential benefits and large scale trials to further evaluate their efficacy are on-going, for example in the United Kingdom (UK) The Northumbria Healthcare National Health Service (NHS) trust is undertaking a 5 year trial with stroke patients using the MIT-MANUS to evaluate improvement in upper limb function. In such a multidisciplinary area of research there is the potential to develop rehabilitation robots, which have not drawn upon the research previously conducted in this area or related disciplines. This can lead to sub-optimal systems, which do not maximise the quality of therapeutic exercise or worse still are not utilised because of poor design. Furthermore, as a community are we confident that rehabilitation robotic technology is suitably mature to conduct large scale efficacy trials? The danger in evaluating technology before suitable maturity is that it is set up to fail and as such starved of investment and development stifled. Clearly we need to consider carefully the design requirements for upper limb rehabilitation robotic technology drawing on our current knowledge.

In this paper we aim to highlight some important design considerations for upper limb rehabilitation robots and highlight relevant literature with the objective of stimulating discussion with the community and providing a resource for those interested in developing such technology. We do not intend on providing an exhaustive list of design considerations but instead present our opinion of important design factors and highlight where we believe our focus should be.

2 What to consider when designing rehabilitation robots

2.1 The need for a multidisciplinary team

Rehabilitation robotics is a multidisciplinary field and as such if this technology is to successfully develop it will require specialists from a number of disciplines to be involved in its design. Figure 1 illustrates the discipline's that have specialist knowledge/skills that will benefit the development of rehabilitation technology. Without input from a number of disciplines, key requirements of the system may be omitted in its design.

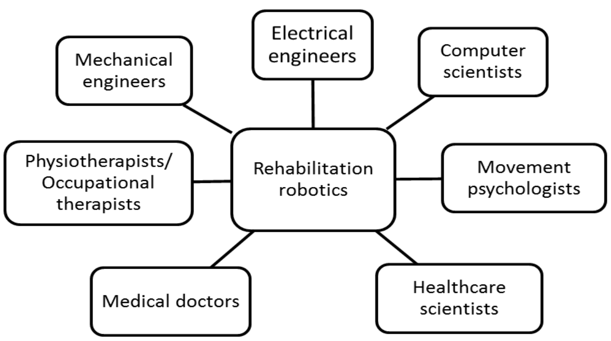

Figure 1: Illustrating the disciplines that have specialist knowledge/skills that can benefit the development of rehabilitation robotics.

2.2 Engage the end users in the design process

The User Centred Design (UCD) process involves engagement with end-users to determine their desires, requirements and limitations through a variety of methodologies to successfully develop technology that meets these requirements. The term end-user refers to the people who will utilise the technology, in the case of rehabilitation robotics; this includes the neurologically impaired, therapists and medical doctors. However in this context this term is often extended to include anyone associated with the utilisation of this technology, for example family members of the neurologically impaired.

In the UK the NHS, and the wider healthcare community, we have seen an increased emphasis on the need for user involvement within healthcare research to ensure the issues of importance to end users, and not just those of academic or clinical interest are addressed (Lightfoot and Sloper, 2003, Shah and Robinson, 2006, Hogg, 2007, Lamey and Bristow, 2007). Shah & Robinson, 2006, from the Multidisciplinary Assessment of Technology Centre for Healthcare (MATCH), emphasise that gathering users' needs has been shown to determine both the success/failure of the development of technology (Shaw, 1998), and the quality associated with the product (Keiser and Smith, 1993). Furthermore, researchers such as Bridgelal, et al., 2008 go on to say that involving users throughout the cycle of device development, "…increases the likelihood of producing devices that are safe, usable, clinically effective and appropriate to cultural context".

Rehabilitation robotics requires the merging and integration of the technical capabilities of the technology with the desires of the end users in order for it to be successful. Shah and Robinson, 2006 highlighted a number of methods that have been utilised for medical device development, including usability tests, focus groups, observation, and simulations.

Several authors have utilised a UCD approach with end users to identify design issues in rehabilitation robotics including (Lee, et al., 2005, Holt, et al., 2007, Lu, et al., 2011). Lee *et al.,* 2005 conducted a survey with physiotherapists to identify design issues, highlighting the importance of safety, cost, privacy of patient information and intuitive usability, concluding that in general therapists respond positively to the idea of rehabilitation robotics. Lu *et al.,* 2011a presented a UCD approach for the development of a robot for upper limb rehabilitation of adults with stroke whilst Holt *et al.,* 2007 suggest that user involvement for developing rehabilitation robotics is an essential requirement.

The development of rehabilitation robotics for children presents a unique design challenge that can make conventional methods to engage users challenging. There is a sparsity of literature for the development of rehabilitation robotics for children using a UCD approach; however research by Holt *et al.,* 2013, Weightman *et al.,* 2010 present useful methodologies and highlight their opinion of the importance of such an approach.

In summary, analysis of the literature illustrates that adopting a user centred design approach is beneficial in developing effective rehabilitation robotic technology.

2.3 Consider the required functionality

We have already considered the importance of UCD, in this section we will consider some important functionality of rehabilitation robots identified using this technique. We can categorise the functionality for rehabilitation robots into five areas, therapeutic functionality, mechanical functionality, safety, motivational factors, user friendliness and social acceptability (Weightman, et al., 2010). We will consider rehabilitation robotic control in a later section of this paper.

Therapeutic functionality

The type of arm exercise the rehabilitation robot should promote and how these match the movements physiotherapists would encourage should be considered. Brewer et al., 2007 advocate further research comparing physiotherapy and rehabilitation robotics. However there is research that can aid us in designing rehabilitation robots with consideration to therapeutic functionality.

The versatility of the rehabilitation robot which allows for different patient positions, different arm movements, and different types of exercise is important. Maintaining adequate joint alignment and providing assistive forces proportional to the needs of the patient are two other important functional features. Pain and muscle fatigue detection, could also be used to personalise therapy (Lee, et al., 2005, Lu, et al., 2011).

Mechanical functionality

The mechanical functionality of a rehabilitation robot will be coupled to the required therapeutic functionality. However, the performance including the functional workspace, smoothness of movement and robustness should be considered (Weightman, et al., 2010).

In order to achieve therapeutic adaptability it has been proposed that users prefer for the robot to have an increased number of degrees of freedom and be able to move in different planes (Lee, et al., 2005, Lu, et al., 2011), however this could increase mechanical complexity, weight, size and cost.

Safety

Safety standards can be divided into hardware and software based (Weightman, et al., 2010). Hardware safety design functions include: limiting the range of motion, safe movement protocols implemented because of emergency or danger (Lee, et al., 2005) and having accessible and effective emergency stop switches and buttons.

Software safety features include safe control algorithms that adapt therapy to patient needs and limits, automatic safety checks, having audio-visual warnings in case of danger or failure (Lee, et al., 2005), effective information sharing between machine and user (Tejima, 2000) and security over personal data of the patient (Lee, et al., 2005).

Other good design practices and recommendations regarding safety include quantitatively evaluating the effectiveness of safety strategies and working towards safety oriented design based on human pain tolerance. (Tejima, 2000)

Motivational factors

Several factors can influence patient motivation, including patient age and preferences, and as such improve adherence to prescribed exercise. (Maclean, et al., 2002, Colombo, et al., 2007) Other motivational features can be valuable: providing audio or visual positive feedback for encouragement alongside progress visualisation (Lee, et al., 2005). Computer game motivational factors will be considered in more detail later.

User friendliness and social acceptability

User friendliness is a key component in the design of rehabilitation robots. For example in home or school environments poor user friendliness is likely to lead to poor utilisation (Holt, et al., 2013, Preston, et al., 2014). User friendliness can be considered the ease with which the device is utilised. Factors that affect this include the size and set up time. Research would indicate a preference for a set up time less than 5 minutes, allowing for portability, and having a simple to use software and user interface. (Brewer, et al., 2007, Weightman, et al., 2010, Holt, et al., 2013)

Social acceptability in this context is how the rehabilitation robots are perceived by users and others. This is of particular relevance for rehabilitation robots for children with cerebral palsy, children with a perception that the device is for rehabilitation may not want to use it. (Weightman, et al., 2010)

2.4 Design for the environment the rehabilitation robot will be used in and consider the cost/benefit trade offs

Robotic devices for upper limb rehabilitation

A recent review by Maciejasz, et al., 2014 highlighted the plethora of rehabilitation robots that have been developed. Classification of the type of robot has been based on the type of actuation (Gopura and Kiguchi, 2009) and the manner in which the robot attaches/guides the arm (Maciejasz, et al., 2014). The wide variety of rehabilitation robots is a reflection of the differing requirements in terms of the clinical condition they are designed to provide therapy for and also the environment in which the therapy will be delivered.

What environment will the robot be used in

The environment in which the robot will be used is important in its design. Important parameters to consider include the size, weight, usability, portability and power requirements, as this will be subject to the environmental constraints. For example a home environment will place more of a constraint on size than a rehabilitation robot designed for a clinical environment.

Researchers in this field seeking a more detailed analysis may find the work of Jackson, et al., 2007, Weightman, et al., 2011, Holt, et al., 2013 who have deployed rehabilitation robots in clinical, home and school environments respectively.

The environment in which the rehabilitation robot will be used will influence the type of actuation of the robot. There are three different types of actuation being used in the robotic rehabilitation systems namely, electric motors (Krebs and Hogan, 2006), pneumatic actuators (Secoli, et al., 2011) and hydraulic actuators (Stienen, 2007). Electric actuators are the most popular choice for such applications (Maciejasz, et al., 2014). This is mostly due to the fact that electric motors have a relatively higher power output and they are easy to power and control.

Conversely, pneumatic actuators are lighter and have lower impedance but they are hard to control due to their non-linear nature (Harwin, et al., 1995, Morales, et al., 2011). In addition, despite the small size of the actuators the overall size of a pneumatic system is dramatically increased by the size of the compressor needed to provide them with pressurised air (Maciejasz, et al., 2014). For all the aforementioned reasons such systems are most suitable for application where they remain stationary such as clinical environments.

Finally, hydraulic actuators have been the less popular choice amongst all three. Such actuators have a high torque output and are very sensitive and responsive (Maciejasz, et al., 2014). On the other hand they require frequent maintenance, are prone to oil spillages and they require a lot of space thus making them unsuitable for robotic rehabilitating applications (Gopura, et al., 2011).

The physical interface between robot and patient

The manner in which the robot attaches to the patient is important as it will determine if the robot promotes desirable spatial and temporal characteristics of the end point (hand) or the arm. We should consider the environment in which the robot is to be deployed as large multiple point of attachment systems are suited to clinical environments and not home based rehabilitation. Similarly end point of attachment robots may be better suited to home based rehabilitation but in clinical environments the advantage of promoting desirable movements of the whole arm and not just the end point may be favourable.

Single point of attachment systems

The most common design of such systems are end effector/endpoint systems. These systems are usually attached to/held by the patients hand (Loureiro, et al., 2011). Such systems are usually more simplistic, less expensive, are usually portable and have a smaller footprint hence making them ideal for home rehabilitation applications. Furthermore, due to their simple configuration such systems require less complicated control algorithms. On the other hand, such systems can only control the position of the hand and not the corresponding position of the elbow and shoulder hence allowing configuration that may potentially injure the arm (Loureiro, et al., 2011, Maciejasz, et al., 2014).

A recently conducted review of robotic devices used in upper limb rehabilitation by Maciejasz *et al.,* 2014 identified that the majority of the single point of attachment systems developed, allow movement in three dimensions. However, several systems have been developed that only allow movement in a single plane. Such systems, are very simple and economical and when combined with carefully selected control algorithms allow similarly effective movements with their three dimensional counterparts (Loureiro, et al., 2011).

Multiple point of attachment systems and exoskeletons

Such systems can control the full kinematics of the human arm. They allow the control of posture during movement and control of the synergies between the joints by allowing or prohibiting certain configurations (Gopura, et al., 2011). Furthermore, because of their ability to very accurately follow the movement of the human arm they provide very efficient means to collect kinematic data in real time. Conversely, such systems are usually big, utilise multiple actuators, are more complicated to design and control and hence are more expensive than single point of attachment systems. For all the aforementioned reasons such systems are more suitable for the clinical environment such as hospitals and rehabilitation centres. (Lo and Xie, 2012, Maciejasz, et al., 2014).

Cost/Benefit trade offs

As we have seen there are advantages and disadvantages to different robot configurations and corresponding actuation systems which define their suitability for different environments. As such when we consider the design requirements for this technology they will be different depending on the intended environment it will operate in. Hence cost/benefit analysis in terms of the selection of the type of robot configuration and actuation system should be considered. For example, if we are striving as a community to develop rehabilitation robotic technology for home use should we not consider the choice of components, benefit of additional degrees of freedom and complexity with respect to cost. Home based rehabilitation robotic systems have to be economically viable for healthcare providers so, as a community, should we not be integrating this into our design requirements?

2.5 Design a motivational game

Development of rehabilitation robotic systems has mainly focused on the hardware development of the system and not the game element (Shah, et al., 2014). Developing the motivational game component of a rehabilitation robot can increase the amount of therapy undertaken by the patient and conversely a poorly motivating game is likely to reduce the amount of therapy undertaken (Colombo, et al., 2007). Should we not review out focus on the software element as without it the most advanced hardware will not be utilised.

Unlike therapy utilising the Nintendo Wii or XBOX Kinect rehabilitation robotics cannot utilise commercially available games as the controller implemented to determine the forces applied to the patient applies more constraints. As such the design of rehabilitation robots needs to consider the type of motivational game developed carefully. Several researchers have highlighted the need for a better computer game element for rehabilitation robotics systems (Dickey, 2005, Colombo, et al., 2007, Fluet, et al., 2010, Weightman, et al., 2011, Preston, et al., 2014, Shah, et al., 2014)

Lohse et al., 2013 state that designing a video game for rehabilitation purposes is a multidisciplinary task including game design, neuroscience of motivation and principles of motor learning. Several key considerations have been identified in the literature which the designers of computer games for rehabilitation robots should be aware of:

Game interface

Cook, et al., 2002 highlighted the easier the gaming interface the better understood by the patient in their research with children with severe disabilities.

Set clear goals

Both long-term and short-term goals are essential in providing an objective to strive for and can divide a lengthy task into manageable sections (Fullerton, 2008). Gameplay can be considered as offering two major categories of goals, self-improvement or survival (Lohse, et al., 2013). Self-improvement can be considered as reaching a new stage ("level") of a character/avatar and acquiring fictive material goods. Survival goals can be considered as a consequence of failing a given task, leading to reattempting the task or restarting the game. Some studies suggest that the lack of long-term consequences may lead to increased perseverance, provoking users to use different strategies. (Hoffman and Nadelson, 2010)

It has been shown that goal oriented tasks lead to an increased motivation and engagement. (Lohse, et al., 2013)

Rewards and achievements

Rewards and achievements (feedback) act as positive recognition for finishing a given task and are common to computer games. It has been observed that after being presented with a reward or acknowledgement after a challenging action, users feel a sense of gratification and are more likely to continue playing the game. (Lohse, et al., 2013, Shah, et al., 2014)

Difficulty/Challenge

The level of difficulty of a game can greatly affect the willingness to continue playing (Colombo, et al., 2007, Shah, et al., 2014). If the level of challenge is too low the player can lose motivation and conversely if the task is too challenging the user is more likely to abandon playing altogether. (Hoffman and Nadelson, 2010)

So what is an appropriate level of challenge? (Lohse, et al., 2013) define the concept of "positive failure" stating that it is more motivating to fail just before accomplishing a task as the user is more likely to reattempt it. Lohse et al., (2013) suggest steadily increasing the level of difficulty of a task allowing for greater transfer of skills from one challenge to the next, finally leading to a transfer to everyday activities. They also suggest this can be accomplished by maintaining the user at the limit of his/her ability throughout the game.

Furthermore using steadily increasing levels of difficulty allows for a greater transfer of skills from one challenge to the next, finally leading to a transfer to everyday activities. This can be done by maintaining the user at the limit of his ability throughout the game. (Lohse, et al., 2013)

Choice, Interactivity and Control

Choice (options) within computer games refers to the ability of taking different paths or strategies in order to attain a desired result. This can lead to players attempting to replay a game after completing it, in order to try a new perspective. (Lohse, et al., 2013) suggest that there is a strong link between exploring new possibilities in-game and physiological rewards. However this may be difficult to implement as the control of the robot may impose constraints.

(Hoffman and Nadelson, 2010) suggest free control of the game environment is also important. The ability to make decisions offers positive feedback irrespective of failure or success.

Socialisation

Lohse, et al., 2013 emphasise the importance of creating a social environment around games, and identify three types, competition, feedback and presence. The first two provide a direct interaction between users, either competing or supporting each other in order to achieve the given goals. The latter does not require contact, the existence of other players in the same environment provides comfort (Holt, et al., 2013).

Lohse, et al., 2013 suggest that when considering rehabilitation, socialisation through an online community can lead to an increased amount of time spent using the device.

Context

Hoffman and Nadelson, 2010 highlight the importance of, but not essential, high end graphics and an appealing story line. The authors state that a focus on function related features should gain priority.

2.6 What control strategy should be used?

The control strategy can be considered as the manner of interaction between the user and the rehabilitation robot. The control strategy used for rehabilitation robotics is critical (Reinkensmeyer, et al., 2004, Marchal-Crespo and Reinkensmeyer, 2009, Alexoulis-Chrysovergis, et al., 2013) as its function is to promote motor learning/relearning of the upper limb. Analysis of the literature illustrates a variety of different control strategies have been utilised, Marchal-Crespo and Reinkensmeyer, 2009 suggests the control strategies can be characterised into three groups, see Figure 2.

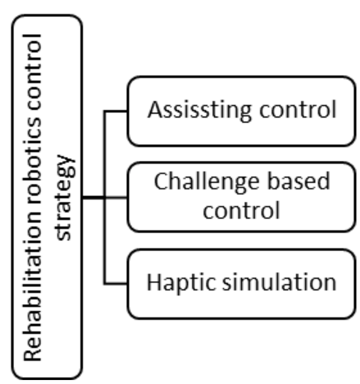

Figure 2: Illustrating the categorization of control strategies as proposed by (Marchal-Crespo and Reinkensmeyer, 2009)

Assisting control

Assisting control strategies are similar to "active assist" type exercises that physiotherapists utilise that help to move the impaired limb in aiming type movements, they are the most predominately utilised control strategy (Marchal-Crespo and Reinkensmeyer, 2009). However, literature has highlighted that this type of controller can reduce the amount of volitional control from the patient leading to a decreased effort (Wolbrecht, et al., 2007). To overcome this problem "assistance as needed' controllers aim to only assist as much as needed encouraging the patient to increase effort levels. Methods used to implement this include triggering assistance at set force/velocity thresholds and dead bands, that is areas in which no assistance is provided.

Challenge based control

Challenge based control strategies augment the error between the actual and desired trajectories or promote increased effort. This type of strategy includes providing resistance to the patient's movement (Hesse, et al., 2003) promoting increased effort. Furthermore error augmenting control algorithms (Alexoulis-Chrysovergis, et al., 2013) have been shown to influence motor adaptation (Wolpert, et al., 1995) and improve motor function in adults suffering from stroke (Morris, et al., 2004, Patton, et al., 2006).

Haptic simulation

Haptic simulation strategies involve the practice of activities of daily living within a virtual haptic environment (Montagner, et al., 2007, Marchal-Crespo and Reinkensmeyer, 2009). These types of environment can create many simulations of real life situations giving an appropriate context to the movements being practiced and automatically grade the level of difficulty. (Patton, et al., 2004, Nef, et al., 2007)

Summary

Rehabilitation robotic control is an on-going area of research, currently research is being conducted with a number of different strategies, although it is not clear which is the optimal for promoting motor learning/re-learning. It is plausible that different controllers will be more suited to different levels of severity of neurological impairment. In the authors opinion further research is required in this area before large scale clinical trials are conducted.

2.7 Consider feedback that may improve performance

Although different approaches have been undertaken by different research groups the main concept behind rehabilitation robotics is that a robotic system interfaces with is the patient's impaired limb then, the patient is asked to perform predefined tasks, usually interacting with a computer interface. The system provides visual, auditory or audio-visual feedback in the form of a computer game while a control algorithm determines the systems response to the patient's movement, given the information provided by a setup of different sensors, such as accelerometers, dynamometers, EMG signals etc.

A significant amount of research in this field has focused on the controller design as we have discussed in the previous section. However, an equally important aspect is the selection of the type and form of feedback that is provided to the user. Appropriate feedback can motivate the user reducing abandonment and also provide the user with useful information about their performance. In this section we will present relevant literature relating to the different types of feedback that can be used in upper limb rehabilitation robotics and its effect on motor learning for the impaired.

Feedback can be categorised as intrinsic and extrinsic. Intrinsic feedback is a result of the sensory information generated by an individual's own movement while extrinsic or augmented feedback is information externally given to the individual. The latter can be provided in different forms namely visually, acoustically or haptically (Van Vliet and Wulf, 2006). There has been sufficient evidence that extrinsic feedback can improve motor function, promote motor learning and increase retention of an acquired skill (Van Vliet and Wulf, 2006). However, the positive effect of extrinsic feedback on improving upper limb function is influenced by the type of feedback, the stage of the trial that this is provided and the information that is provided to the user with as illustrated in Figure 3.

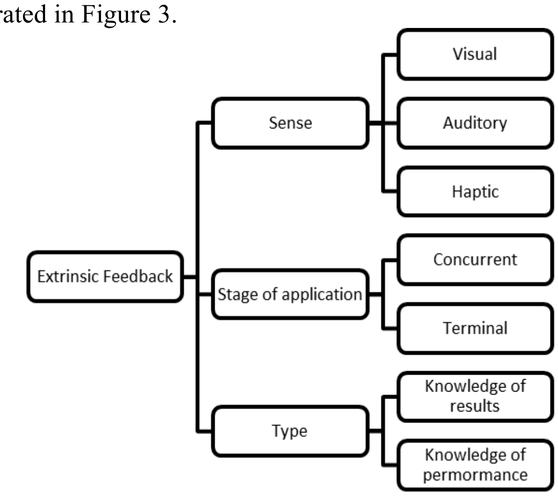

Figure 3: Different parameters of extrinsic feedback on upper limb rehabilitation

Type of feedback

Visual feedback, via a computer screen, virtual reality system, or augmented reality system, is the most commonly used type of feedback and is sometime used in conjunction with auditory feedback. There has been evidence of the benefits of visual feedback when provided in a carefully selected manner (Molier, et al., 2010, Parker, et al., 2011, Patton, et al., 2013)

Auditory feedback has been a rather understudied source of feedback. Recently there has been sufficient evidence presented in literature that auditory feedback promotes brain plasticity through mechanisms that are fundamental for the recovery from neurological injury (Rosati, et al., 2013).

Sigrist, et al., 2013 state that "haptic feedback is defined as any kind of haptic perception that teaches the necessary features that guide the subject toward, and not necessarily through, the desired motion". Haptic feedback has been found to enhance participation and cooperation and promote motor learning (Sigrist, et al., 2013)

When should feedback be given

An important factor to consider is whether augmented feedback should be provided during (concurrent) or at the end of each trial (terminal). Concurrent feedback has been shown to have a positive effect on motor learning and skill acquisition. However, it has been observed that when only real-time concurrent feedback was provided the performance has reduced on follow-up retention tests (Park, et al., 2000). This is has been attributed to patients becoming highly dependent on the feedback provided (Sigrist, et al., 2013).

Park, et al., 2000 suggest that concurrent feedback may only be useful in the early stages of a training scheme where the patient needs assistance in understanding the task needed to be performed and that it should be switched off in the subsequent trials. An alternative is to only provide feedback at the end of a trial. This has been shown to reduce dependency but not eliminate it. As such, trials where no feedback is provided are required in order to strengthen the internal movement representation. (Sigrist, et al., 2013)

Information

Another important aspect of feedback is the information it communicates to the user. This information can be categorised as Knowledge of Results (KR) and Knowledge of Performance (KP). Knowledge of results is information about the outcome of performing a skill or about achieving the goal of the performance. Knowledge of performance is information about movement characteristics that led to the performance (Timmermans, et al., 2009). In early stages of therapy prescriptive KP seems to be more beneficial, while in more advanced stages of therapy descriptive KP appears to be more constructive (Molier, et al., 2010).

The literature demonstrates that designers of rehabilitation robots should consider the manner in which feedback is given in order to potentially improve performance.

3 Discussion

The aim of this paper was to highlight some important considerations in the design of rehabilitation robots for the neurologically impaired. Analysis of the literature has demonstrated there are several important areas of current interest.

Analysis of the literature has illustrated that rehabilitation robotics designed by multidisciplinary groups utilising a UCD approach have been successfully deployed in clinical, home and school environments.

This paper has presented a number of key functionalities that have been highlighted in previous literature that designers of rehabilitation robots should be aware of and consider in the design of future technology.

Furthermore we have highlighted the importance of designing a rehabilitation robot for the environment it will be used in and to focus on the cost/benefit trade offs. If as a community we wish to promote the commercialisation and hence adoption of such technology, should we not be designing rehabilitation robots that are focussed on both improved performance and reduced cost? The cost of the technology will be a crucial factor in the decision making process of healthcare providers in determining its feasibility.

We have presented literature which supports our opinion that we should focus on the development of motivational computer games as well as the rehabilitation robotic hardware. State of the art effective rehabilitation robotic hardware will not be utilised by patients unless there is a motivational computer game to encourage adherence with prescribed therapy.

This paper has demonstrated the significant research that is on-going in the development of control algorithms for promoting motor learning/relearning through rehabilitation robotics. This is a challenging area of research as significant time and funding is required to trial control algorithms with rehabilitation robotics with the neurologically impaired. Furthermore, it is even more challenging to assess the effectiveness of one control strategy in relation to another. The problem is further compounded when we consider that for neurological impairments such as stroke or CP we cannot consider this population as a group with a homogenous type of impairment, each individual will have their own specific characteristic neurological and physiological impairments with varying degrees of severity. In the authors opinion we must investigate this area in breadth and depth before we can expect efficient effective rehabilitation robotic technology for the neurologically impaired.

Finally we have presented literature that illustrates the importance of providing feedback to patients utilising rehabilitation robotics and how it can be used to improve outcomes.

3.1 Future directions

We have highlighted essential literature that should be considered for the design and development of rehabilitation robotics. There are numerous challenges to the future development of rehabilitation robotics if they are to be effective and economically viable for healthcare providers. The following paragraphs highlight some areas of importance for the future development of rehabilitation robotics.

Home based systems

Predominately rehabilitation robotic systems have focussed on the development of systems for use in clinical environments. These systems have demonstrated benefit for improving upper limb function of the neurologically impaired. However the inherent problem with these systems is that patients have to travel to hospitals to use them and as such this reduces access to a large volume of useful therapy. The development of home-based rehabilitation robotic systems has its own challenges including the trade off between functionality and cost as well as the logisitcal support of patients using the home based systems. However, these systems would enable a greater volume of useful therapeutic exercise to be undertaken in comparison to clinically based systems.

Methodological quality of research

There are several measures of methodological quality that have been developed for assessing the quality of published research in the healthcare domain. However these measures are predominately focussed on the trial of medicines and are ill suited for assessing the quality of literature in the area of rehabilitation robotics. Without a more appropriate measure of the quality of research it is more problematic to assess the contribution of research studies and as such more difficult to draw valid conclusions from the available literature.

Adoption and Integration of rehabilitation robotics

Although there is limited literature in the area, the adoption of upper limb rehabilitation robotics into healthcare provision has been limited, concerns about the cost of the technology are not straightforward according to economic analysis [Turchetti, et al., 2014]. We believe there is another barrier to the technology that should be considered, namely how will such technology integrate into existing healthcare provision structures? If the technology is to be home based then it may be that additional technical support will be required to support the implementation of the therapist prescribed interventions. Where will this technical support come from and how will this role integrate into existing infrastructures? As a community do we need to develop a suggested model for adoption to inform decision makers?

4 Conclusions

Rehabilitation robotics has shown potential for providing increased access to rehabilitation for improving arm function in the neurologically impaired whilst also being economically viable for healthcare providers. It would seem sensible to continue our efforts as a community in seeking answers to important design considerations, such as those highlighted in this paper, before embarking on evaluating the overall efficacy of rehabilitation robotics for promoting motor learning/relearning in the neurologically impaired.

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