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CHAPTER 10

Technology improves upper extremity rehabilitation

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Abstract: Stroke survivors with hemiparesis and spinal cord injury (SCI) survivors with tetraplegia find it difficult or impossible to perform many activities of daily life. There is growing evidence that intensive exercise therapy, especially when supplemented with functional electrical stimulation (FES), can improve upper extremity function, but delivering the treatment can be costly, particularly after recipients leave rehabilitation facilities. Recently, there has been a growing level of interest among researchers and healthcare policymakers to deliver upper extremity treatments to people in their homes using in-home teletherapy (IHT). The few studies that have been carried out so far have encountered a variety of logistical and technical problems, not least the difficulty of conducting properly controlled and blinded protocols that satisfy the requirements of high-level evidence-based research. In most cases, the equipment and communications technology were not designed for individuals with upper extremity disability. It is clear that exercise therapy combined with interventions such as FES, supervised over the Internet, will soon be adopted worldwide in one form or another. Therefore it is timely that researchers, clinicians, and healthcare planners interested in assessing IHT be aware of the pros and cons of the new technology and the factors involved in designing appropriate studies of it. It is crucial to understand the technical barriers, the role of telesupervisors, the motor improvements that participants can reasonably expect and the process of optimizing IHT-exercise therapy protocols to maximize the benefits of the emerging technology.

Keywords: stroke; spinal cord injury; multiple sclerosis; upper extremity; telerehabilitation; in-home teletherapy; functional electrical stimulation; upper extremity rehabilitation.

Introduction

Three million stroke survivors in North America have unilateral paresis of the upper extremity (Lloyd-Jones et al., 2009). Over 100,000 people living with spinal cord injury (SCI) have bilateral paresis or paralysis (NSCISC, 2010). People with tetraplegia due to SCI often depend on caregivers to perform the simplest manual tasks. Recovery of upper extremity function is their top priority, over all other disabilities (Anderson, 2004).
A rigorous program of exercise therapy can improve upper extremity function after stroke and SCI (Drolet et al., 1999), and small improvements can make a large difference (Beekhuizen and Field-Fote, 2005). However, ensuring compliance to a regular exercise therapy program after people leave rehabilitation facilities is challenging. Clients may be given lists of exercises they should perform, but these tend to be boring and compliance drops off over time. Health-care systems cannot afford to pay for home visits by therapists to supervise exercise therapy. This unsatisfactory situation has given rise over the last few years to some new methods of delivering upper extremity rehabilitation. These include forced-use training, now known as constraint-induced movement therapy (Taub et al., 2006), computerized exercise devices such as the Nintendo Wii, robotic devices that apply forces to the arm to assist or resist movements (Volpe et al., 2009), therapeutic electrical stimulation and functional electrical stimulation (FES; Peckham and Knutson, 2005; Stein and Prochazka, 2009) and in-home teletherapy (IHT) supervised over the Internet (Gritsenko and Prochazka, 2004; Gritsenko et al., 2001; Kowalczewski et al., 2011; Krebs et al., 1998; Reinkensmeyer et al., 2011).

IHT delivered to participants, particularly when combined with interventions such as FES, poses unique safety and legal challenges which must be resolved before the technology is made available to the larger population (Cooper et al., 2001). Nevertheless, with an aging population and ever-decreasing technology costs, telesupervised rehabilitation will most likely provide an important alternative to traditional rehabilitation. Little information has been published on the obstacles that may arise when implementing IHT and how they can be overcome. In this chapter, we will discuss some of the technical problems we encountered in a recent clinical trial involving IHT and FES.

The descriptions and opinions presented here are based on the experiences acquired in a randomized clinical trial (NCT00656149, www.clinicaltrials.gov). In this trial, we compared two levels of FES-exercise therapy and IHT treatment in people with SCI. The main results of this study have been published elsewhere (Ellaway et al., 2010; Kowalczewski and University of Alberta, Centre for Neuroscience, 2009; Kowalczewski et al., 2011).

General issues

Clinical studies of rehabilitation treatments, particularly when these are telesupervised, differ from clinical trials in other fields. First, most researchers planning randomized controlled trials in rehabilitation, struggle with a suitable design, as in this field it is often difficult to provide quantitative outcome measures, blinded assessments, control treatments that are not obvious to the participants and therapists and even suitable randomization, given the variability between people with the same basic disability. It has been pointed out that in the whole field of rehabilitation, there has been only a handful of studies that have fulfilled all the criteria of high-level, evidence-based studies (Johnston et al., 2006). Second, the equipment required for IHT has to be designed in such a way as to withstand daily use for the duration of the trial, yet be intuitive and simple enough to be used by impaired participants without the constant presence of an able-bodied person to aid in the rehabilitation process. Further, IHT equipment linking a therapist to a participant has unique requirements compared to the commercial teleconferencing equipment primarily used for conference discussions. Third, if FES is involved, the FES equipment must be easy for the participant to don, doff, and control, and be safe and robust enough to survive rough handling in the home environment. Laboratory prototypes are generally not built with this in mind. Finally, if the therapy is performed at home in the absence of daily supervision, compliance over days and weeks is a major issue, requiring careful attention.
to the entertainment value of the treatment. Therapists providing telesupervision should closely monitor fatigue as this tends to demoralize participants. Fatigue can easily be overlooked in a telerehabilitation setting.

Evidence-based rehabilitation

Only recently has the field of rehabilitation been examined according to the standards of evidence-based treatment through clinical meta-studies such as Spinal Cord Injury Rehabilitation Evidence (www.icord.org/scire) and the Evidence-Based Review of Stroke Rehabilitation (www.ebrsr.com). Rehabilitation therapists have been relatively slow in providing evidence-based care to clients compared to practitioners in other medical fields for a number of reasons. Rehabilitation relies heavily on customization; therapists frequently are faced with unique injuries and obstacles that require patient-specific adaptation of protocols and equipment. This customization is difficult to validate scientifically, unlike medical interventions in conditions with fewer variables. It has generally been difficult in rehabilitation to reach a consensus on the best course of a particular treatment, as it is often impossible to run properly blinded and controlled clinical trials. Unlike pharmacological trials, where placebos can be given to the control group of patients in a double-blind protocol, in rehabilitation trials, the rules of human experimentation require full disclosure to participants of the treatments to be compared (Boutron et al., 2007). If a given treatment is compared to “standard care” or a “placebo treatment,” participants quickly recognize whether they are in the treatment or control group and adjust their expectations accordingly. It is therefore preferable to compare different intensities of a given treatment, where the relative outcomes are genuinely not predictable (Kowalczewski et al., 2007a) or to compare two plausible treatments, for example, a novel intervention and a more conventional treatment that is additional to normal care (Mangold et al., 2009).

It is clear from the above that to run proper evidence-based rehabilitation trials, researchers have to be creative in designing and randomizing their trials (Komaroff and DeLisa, 2009). Rehabilitation also usually takes a substantial amount of time, so treating enough participants to achieve statistical significance can be extremely costly. It is therefore vital for the field that researchers concentrate on designing the best possible randomized controlled trials so as to maximize the chance of influencing clinical practice.

Exercise equipment: efficacy, affordability, quantified outcomes

Conventional exercise therapy has focused on the manipulation of simple objects such as blocks, stacking cones, therapy putty, and so on. Exercise therapy sessions are boring and in the absence of supervision, compliance falls off quickly, particularly at home. Performance is rarely if ever quantified. This began to change with the development of robotic rehabilitation devices instrumented with sensors (Krebs et al., 1998; Volpe et al., 2009). The simplest rehabilitation robots are motors that impose cyclical motion on extremities. They are commonly used in orthopedics (Salter, 1996) and occasionally in stroke and SCI (Dirette and Hinojosa, 1994). The MIT-Manus (interactive-motion.com) is a robot that supports the arm and applies forces in the horizontal plane to assist or resist tracking of virtual objects on a computer monitor (Aisen et al., 1997; Hogan et al., 2006). A recent randomized controlled trial concluded that upper extremity function in chronic stroke subjects improved as much, though not more, after MIT-Manus robotic exercise therapy as after usual care by therapists (Lo et al., 2010). An editorial on the project concluded that the potential for robotic therapy after stroke was enormous (Cramer, 2010). The KINARM (bkintechologies.com) is another example of a planar robotic device that supports the arm. The Motorika ReoGo (motorika.com)
is a telescopic device similar to a floor-shift gearstick, which applies forces to the hand in 3D space. None of these robots exercise dexterous hand movements. The Inmotion 3.0 wrist robot, the Inmotion 5.0 hand robot, and some experimental robots address this deficiency to some extent (Hesse et al., 2006; Lambercy et al., 2007; Popescu et al., 2000). The above devices all cost over $50,000 and so are unaffordable for IHT-exercise therapy. The only affordable robotic device, at around $7000, is the Columbia Scientific “Hand Mentor.” However, this device only exercises wrist and finger flexion-extension movements and ignores range of motion of the whole arm.

Some groups have attempted to deliver motor rehabilitation in the home setting, with conventional exercises (Holden et al., 2007; Piron et al., 2004), therapeutic electrical stimulation (Alon et al., 2003; Sullivan and Hedman, 2007), or simple robotic devices (Johnson et al., 2008; Reinkensmeyer et al., 2002). It has become clear that great efforts must be made in designing usable rehabilitation equipment, as participants in such trials are not able-bodied. In two previous trials, we set out to design and test instrumented workstations suitable for in-home use (Gritsenko and Prochazka, 2004; Gritsenko et al., 2001; Kowalczewski et al., 2007a,b) but we found that there were significant deficiencies in the devices. The first device (Fig. 1a) comprised a desk with a number of instrumented objects chosen to represent household items: a spring-loaded door-knob, a handle attached via a cord and pulley to an adjustable set of weights, rectangular blocks and a cylinder designed to be transferred between two docking bays. This workstation had loose items that tended to be dropped, the layout made some of the items hard to reach, the device was bulky and not easily manufactured. In the next version (Fig. 1b), the items were mounted on a “Lazy Susan,” the idea being that the participant could rotate the device to bring a given item within easy reach. Unfortunately participants were not strong enough to rotate the assembly, loose objects still fell and the structure was even more bulky. We concluded from these attempts that any equipment destined for use in a home setting would have to be of a size that suits the limited amount of space in participants’ homes; the motor tasks would have to take into account the participant’s disabilities and residual motor skills and all items should be in easy reach.

The next attempt comprised a table-mounted “suitcase model” comprising a set of “task modules” attached by compliant cables to docking ports (Fig. 1c). Each module could be pulled out of its docking port, positioned, and stabilized with the less affected hand. This version was significantly cheaper to manufacture and it was reasonably successful in tests on a number of stroke patients; however, a major limitation was the restriction of tasks to a horizontal plane. Further, the device was not suitable for people with bimanual deficits as it depended on tasks being stabilized with one hand while training the other.

By now it had become clear that a portable device was needed that would present the user with tethered, instrumented objects that could move within the full 3D physiological workspace of the hand. Further, the device would ideally provide interesting games that would make exercise sessions enjoyable. We decided to adopt and extend the approach of Reinkensmeyer et al. (2002) who used a commercially available joystick in a computer gaming environment. The range of motion of consumer computer joysticks is very restricted. To extend the range, we fabricated a joystick that had a telescopic shaft and a gimble joint at its base (Fig. 1d). This combination allowed the top of the joystick, which held a number of manipulanda, to be moved through a larger volume. The joystick also contained a sliding card manipulandum designed to train lateral and palmar prehension and push–pull movements like those involved in inserting credit cards into automatic bank machines. Unfortunately, the volume of the workspace was restricted by the lengths of the lower and upper segments of the telescopic shaft, and thus remained significantly smaller than the
full physiological range of the hand of an able-bodied person. It was difficult to maintain the same grasp on the attachments at different shaft angles. Friction within the shaft at oblique angles resisted movement. The only dexterous task on this workstation was the card-sliding mechanism. Some users with restricted ROM could not reach the manipulanda at the top of the joystick, which at its shortest, was still 35 cm above the table surface. The main lesson learnt from this prototype was the importance of positioning the easiest tasks closest to the user so that they were accessible even to low-functioning users.

As a result of all these unsuccessful iterations, we finally settled on a workstation comprising a spring-loaded, segmented arm that presents the user with a variety of attachments representing activities of daily life. We called this the Rehabilitation Joystick for Computerized Exercise (“ReJoyce”). Ten prototype ReJoyce workstations were manufactured and used in our IHT study (Fig. 1e; Kowalczewski et al., 2011). (f) Final version of the ReJoyce system.

Fig. 1. Six versions of an exercise therapy workstation developed for in-home teletherapy. (a) The device used in our first study in chronic stroke (Gritsenko and Prochazka, 2004; Gritsenko et al., 2001); (b) The device used in a study of people with subacute stroke; (c) A table-top system with task modules; (d) A telescopic joystick with attachments; (e) Prototype ReJoyce workstation used in a recent IHT study of people with SCI (Kowalczewski et al., 2011); (f) Final version of the ReJoyce system.
of hand movement. The device allows movement over the full physiological range of an able-bodied person. Each joint and attachment has a sensor that quantifies displacement or force. Signals from these sensors are used to control a suite of computer games which vary widely in subject matter and difficulty. They range from simple games that exercise whole-arm range of motion to games requiring coordinated movements of multiple joints, for example, grasp and squeeze, pinch and lift, grasp and rotate.

The prototype was generally successful but not surprisingly, a number of hardware problems developed over time, requiring home visits for repairs or modifications. On two occasions, air freight was required and this involved assurances regarding the purpose and safety of the devices, which resulted in significant delivery delays. When devices were set up in participants’ homes, in some cases, the table clamps did not have a sufficient range of adjustment for different tables, finding space for the equipment could be problematic in small rooms and connecting to the Internet was occasionally challenging.

The final implementation of the ReJoyce (Fig. 1f), its games and Internet software is the result of 6 years of experimentation. The system may be used with or without telesupervision (see below).

FES equipment

Early studies showed that therapeutic electrical stimulation can significantly reduce hypertonus and improve motor function in stroke survivors (Baker et al., 1979; Taylor et al., 1996; Waters et al., 1981). EMG-triggered FES with hand exercises has since been shown to have beneficial effects (Cauraugh and Kim, 2002; Chae, 2003; de Kroon et al., 2005; Francisco et al., 1998; Heckmann et al., 1997). FES-exercise therapy performed daily for several weeks has been shown to produce clinically significant improvements in hand function in subacute and chronic stroke participants (Alon et al., 2007; Gritsenko and Prochazka, 2004; Kowalczewski et al., 2007a; Popovic et al., 2004, 2005). Several FES devices have been developed for foot-drop (Stein et al., 2006; Taylor et al., 1999; Vodovnik et al., 1981) and some hand FES devices have been developed recently (Hansen, 1979; Nathan, 1994; Prochazka, 1997; Prochazka et al., 1997; Weingarden et al., 1998). Currently, the only commercial FES hand stimulator is the Bioness H200 (Nathan, 1994; Weingarden et al., 1998). It comprises a hinged splint containing pad electrodes, and a separate stimulator triggered by push-button. It costs around $6000, which is out of the range of most potential IHT-exercise therapy clients; however, more affordable hand stimulators are on the horizon.

In the IHT study upon which this chapter is based, two different stimulators were employed. The EMS 7500 surface stimulator was used for therapeutic electrical stimulation. It is an affordable, commercially available consumer device designed to deliver stimuli via self-adhesive gel electrodes placed over appropriate motor points. In our study, we found it necessary to mark the locations of the electrodes on the participants’ forearms to ensure accurate and repeatable placement. A permanent marker was used every 2 weeks to refresh the locations of the electrodes. The placement of the electrodes was most often performed by an aid or family member. After two or three sessions, the electrode gel lost its adherence and so participants were provided with neoprene straps that helped keep the electrodes in place after this occurred.

The other stimulator was a new version of the “Bionic Glove” (Prochazka et al., 1997). The original device was a fingerless glove-like garment containing a built-in stimulator and wettable electrodes. It was controlled by wrist movements. The new version was controlled by the participant, who generated small tooth-clicks to advance the stimulator through a cyclical sequence of three states corresponding to hand opening, grasp, and relaxation (Simpson et al., 2008).
The tooth-clicks were detected by a wireless earpiece similar to a hearing aid. The hanger portion of the earpiece was looped over the ear and held a three-axis accelerometer that rested on the tragus, the small cartilage in front of the ear. When a tooth-click occurred, the earpiece sent a coded transmission to the stimulator in the participant's garment. This caused the stimulator to advance to the next state in the stimulation sequence.

Initially the garment portion of the device was the same as in the Bionic Glove, covering the wrist, palm, and dorsal part of the hand. However, we found that even though the wrist section was compliant, it restricted hand movements. Because we had replaced the wrist movement sensor of the Bionic Glove with the earpiece controller, the palmar portion of the garment was no longer necessary and was replaced with a neoprene loop over the webspace between thumb and index finger which held the thumb adductor electrode in place. This was an improvement, as we have found that covering the palm, even with the use of high-friction materials, increases the likelihood of slip, for example, when grasping and pushing wheelchair rims.

The electrodes were secured by Velcro to the inner surface of the garment, so that when the garment was donned, they were pressed on or close to the desired motor points. The electrode positions within the garment were reevaluated at every laboratory visit. The correct donning of the device required some practice as inappropriate positioning could lead to inadequate or ineffective stimulation. Unlike the adhesive electrodes used in the EMS 7500, the electrodes in the garment needed to be moistened with tap water before each use. Wetting and reconnecting the electrodes to the glove was most often performed by an aid or family member, especially in very low-functioning SCI participants. In contrast, most stroke participants have adequate function of their less affected hand to don and doff stimulator cuffs unaided. Some failures of the hand stimulator occurred initially because the connector between the stimulator and wristlet was exposed and unreliable. This was solved by recessing the connector within a rubberized shoe or “galosh” attached to the wristlet.

**Teleconferencing equipment and software**

We found that one-on-one telesupervision using the Internet was possible with relatively modest software requirements on the supervisors’ and participants’ computers and recurring costs were negligible. Internet-based telerehabilitation requires a minimum of two computers connected reliably to the Internet, webcams, speakers, and microphones or headsets consisting of headphones and a microphone (recommended for echo-cancelation). Standard desktop or laptop computers were used in our study and they had sufficient processing power to handle the large video and audio streams and the custom processor-intensive games that were supplied with the ReJoyce system.

We found that it was crucial to maintain a robust Internet connection. Most participants had a wireless router system in their homes. Remote access from the laboratory to these wireless routers was useful, as electrical storms, router resets and modem resets corrupted the wireless links on several occasions. Remote access generally allowed these problems to be overcome quickly, though on a few occasions a home visit was required. The majority of Internet-related difficulties emerged in the first few days of treatment.

In our trial, we used two types of Virtual Network Computing software. The first, RealVNC® (realvnc.com), implemented a direct computer-to-computer link. The second, Logmein® (www.logmein.com), used a third party server to access the participant's computer, which was more convenient as it did not require the use and configuration of an Internet protocol address, nor the setting up of the participant's router to establish a connection. The drawback to using a third party server is the greater potential for a breach of security (see below).
Various teleconferencing software programs were available prior to this trial, but they were all designed for group interactions. None allowed a therapist to monitor a group of participants and to select particular participants for brief individualized discussions which the other participants did not hear. Software that did provide this ability was developed specifically for the ReJoyce system. It also allowed the therapist remotely to choose games, difficulty levels and the manipulanda involved, for each participant individually. It also allowed an automated, quantitative hand function test to be performed remotely and the data to be downloaded.

Though data and audiovisual streams were encrypted, as with any telecommunication system, it was impossible completely to exclude the possibility of intruders intercepting audiovisual and data transmissions. However, because the custom software was very specialized, restricted to small groups and password-protected, the risk of interception was probably far less than that of public Internet telecommunications protocols, such as Skype, which is used by over 100 million people worldwide. Users and therapists alike were required to accept this risk. Precautions such as avoiding the use of names and places during telesupervision sessions were taken, and will probably remain advisable in all future systems.

Not all computer games were of equal value in our rehabilitation trial. The types of computer games used in upper extremity rehabilitation vary from very simple games (Reinkensmeyer et al., 2002) to virtual reality simulation of real-world tasks with force feedback from haptic devices such as the Phantom robot (Adamovich et al., 2004; Boian et al., 2002). The primary role of a computer game in upper extremity rehabilitation is to increase compliance. Therefore, the games need to be entertaining. They also should ensure that the types of movements involved are beneficial and ideally the games should provide feedback to both the participants and therapists on performance. This feedback can be in the form of an overall score or the time taken to perform a given task. An example of a successful device that provides numerous entertaining games is the Nintendo Wii, which has become popular in rehabilitation clinics for providing range of motion exercises of the whole upper body (Allen, 2007; Graves et al., 2008). However, the Wii was not designed for rehabilitation and its controller does not require or exercise manual dexterity. Nor are the movement signals that control the games available for analysis, though some researchers are working to change this.

Games that provided this type of feedback to the users were among the most utilized by our telesupervisors and the most requested by the participants. Feedback on performance evidently provides a “hook” that plays on the user’s competitive nature. Participants are more inclined to improve on their previous performance when they are provided with a measure of this performance and rewarded for a better outcome. Games that incorporated a reward mechanism had the highest rate of acceptance and usage.

Our trial also suggested that improvements in upper extremity function did not require fully immersive 3D games. All the games developed for the ReJoyce were built with 2D game technology which avoids the need for 3D graphic acceleration, virtual reality displays, or haptics. It was clear, however, that variety in games was crucial. The more games the participant and supervisor could choose from, the higher the chance of the games continuing to appeal to the participants in many repeated sessions. Although preference in computer games has been related to gender in young adults (Lucas and Sherry, 2004) and children (Blumberg and Sokol, 2004), in our trial this was not an obvious outcome, though it would be interesting to study this more rigorously.

Unlike many games designed only for entertainment, the games used in our trial were specifically designed for rehabilitating and retraining upper extremity movements. The advantages of using custom games included the ability to (1) train unique movements that could not be trained on preexisting consumer-oriented games; (2)
modify difficulty settings during the training process in order to optimize the therapy; (3) automatically compute difficulty settings on the basis of a hand function test score; (4) embed the games in the telerehabilitation software suite, minimizing the need to learn how to use non-customized games; (5) design the games to be played with the various manipulanda on the workstation. Six games were developed and used in the trial: a car racing game, a gardening game, a boxing game, a timing game, a target shooting game, and a catching game.

It has become clear in the course of our work that different treatment regimes are needed for different motor disorders. Thus, stroke survivors seemed to benefit most from the training of whole-arm range of motion and finger extension (hand opening) movements, whereas SCI participants benefitted most from training hand grasp and tenodesis pinch-grip.

**Outcome evaluation, effect of fatigue**

The results of the IHT study have been reported in detail elsewhere (Kowalczewski et al., 2011). The primary outcome measure was the widely used Action Research Arm Test (Lyle, 1981; Yozbatiran et al., 2008). Secondary outcome measures included (1) The ReJoyce Automated Hand Function Test; (2) Pinch force between thumb and fingers measured with a pinch gauge (B&L Engineering, Santa Ana, CA); (3) Grasp force measured with a rubberized, instrumented cylinder on the workstation. The ReJoyce Automated Hand Function Test was performed on the ReJoyce workstation with audiovisual prompts and reminders generated by interactive software. Sensors in the workstation provided signals that allowed quantitative scoring of the following variables: range of motion of the hand along three axes (in–out, up–down, left–right), the force of grasp and the amount of pronation and supination during grasp and key-grip. These variables were scored as a percentage of the mean ranges achieved by able-bodied individuals. In addition, there were two functional placement tasks involving grasping, transferring, and releasing two manipulanda on the workstation, one mimicking a soft-drink can and the other a peg. The mean times taken to do several repetitions of these functional tasks were used to obtain a percentage score related to the performance of able-bodied individuals. The mean of all the scores obtained in the above tasks was computed, providing a single overall outcome score. The ReJoyce Automated Hand Function Test took about 5 min to perform.

The scores from both the Action Research Arm Test and the ReJoyce Automated Hand Function Test improved significantly more during and after ReJoyce exercise therapy with FES than after conventional exercise therapy with therapeutic electrical stimulation (Fig. 2). Both protocols involved 6 weeks of 1 h/day IHT. Grasp force also increased more in the ReJoyce group. We concluded that FES-assisted exercise therapy on a ReJoyce workstation, supervised over the Internet with IHT, was feasible and effective. The improvements exceeded the minimal clinically important difference, which is often used as a criterion to introduce a treatment into best practice.

We found that during IHT therapists had to be careful not to overexert participants involved in IHT-exercise therapy. In one case, a participant developed proximal muscle strain that required a rest period of 2 weeks for recovery. Fatigue can potentially aggravate preexisting pain and spasticity as well as cognitive and emotional disorders (Hammell et al., 2009). On the other hand, moderate physical activity in SCI has been shown to lower pain, fatigue, and depression (Tawashy et al., 2009). Therefore, it is important to judge the appropriate amount of exercise on an individual basis.

Muscle fatigue was commented upon by all of the participants in our study. It is known that muscles lose fatigue resistance following SCI (Shields et al., 1997). The loss occurs fairly
Traditionally, muscle fatigability is quantified by measuring the torque generated by an electrically stimulated muscle or group of muscles (Stein et al., 1992). In our IHT trial, no such quantitative measure was available, but it was commonly observed that most participants were unable to complete a full hour of FES-assisted exercise in the first week of ReJoyce training sessions. Initially, muscles would only respond to stimulation for a few minutes. This improved as the treatment progressed and by the second week all participants were able to generate functional movements with FES for the entire 1 h session.

Interestingly, this effect was discernible in the scores of the Action Research Arm Test and ReJoyce Automated Hand Function Test when these were performed before and after 1 h exercise sessions (Fig. 2, solid lines: scores just before exercise therapy, dashed lines: scores just after exercise therapy). Paired Student’s *t*-tests showed significant differences at week 2, but not thereafter, suggesting that the muscles had become more fatigue resistant by week 4. This correlated with spontaneous comments from the ReJoyce group in early training sessions that the games distracted them to the point that at the end of a session they felt that they had had a very vigorous workout. The control group rarely made this sort of comment.

Experiencing rapid muscle fatigue following electrical stimulation in the initial period was discouraging for the participants. During the first 2 weeks, it is therefore important that participants be made aware that electrical stimulation can rapidly fatigue muscles but that with training the muscles build fatigue resistance.

**Conclusion**

Many recent studies have shown that exercise therapy can significantly improve upper extremity function after a stroke or SCI, which implies that currently the duration and intensity of exercise therapy provided to these individuals are insufficient. This is because of the cost and logistical...
difficulties of providing such treatment, particularly after people rejoin their communities. Further, because of time and budgetary constraints, the main focus of many therapists is to teach basic adaptive strategies, self-care, and hygiene and to provide assistive devices and techniques for life at home. Improving hand function is often treated as a desirable but secondary aim. This state of affairs is driven by the increased pressure on healthcare systems and third-party payers to provide patients with only the most elementary coping skills to contain costs and allow for a large throughput. But as suggested by Dr. Kimberley Anderson in a study of SCI priorities (Anderson, 2004), this may be a false economy. The use of affordable technology that allows upper extremity rehabilitation to be performed at home with Internet-based telesupervision provides a promising solution to this dilemma.

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References


