Spinal Cord (2009) 47, 196–203

www.nature.com/sc

REVIEW

Systematic review of the effects of exercise therapy on the upper extremity of patients with spinal-cord injury

MGM Kloosterman[1,2], GJ Snoek[2] and MJA Jannink[2]

[1]*Center for Human Movement Sciences, University Medical Center Groningen, University of Groningen, Groningen, The Netherlands and* [2]*Roessingh Research and Development, Enschede, The Netherlands*

Objective: To assess the effects of exercise therapy (ET) on motor control and functional ability of the upper extremity in patients with cervical spinal cord injury (SCI).
Methods: An extensive systematic literature search in five databases was performed to identify clinical and (randomized) controlled trials, evaluating the effects of ET on motor control and functional ability in patients with SCI. The methodological quality of the selected studies was systematically assessed by three reviewers.
Results: Eight studies were included. Seven had good-to-fair methodological quality, six reported positive effects of ET on motor control (for example, muscle strength or muscle grade) and four also reported positive effects on functional ability. Five of these studies focused on patients with long-lasting SCI. A great variety of therapeutic approaches were applied, even within ET there was a wide range of training characteristics.
Conclusion: Although ET is a cornerstone in the treatment of the upper extremity in patients with SCI, only a small number of studies were included in the present review. Most of the included studies reported a positive effect of ET on upper extremity motor control and functional ability in SCI patients. As ET is effective in patients with SCI in the chronic stage, this might have implications for the follow up and further treatment of these patients. Future studies should be more specific in describing the characteristics of ET to verify that the ET is in accordance with the current standards for training and motor relearning.
Spinal Cord (2009) **47**, 196–203; doi:10.1038/sc.2008.113; published online 30 September 2008

Keywords: exercise therapy; upper extremity; spinal cord injury; motor control; functional ability

Introduction

The worldwide estimate of the prevalence of spinal cord injury (SCI) is 223–755 per million inhabitants, with an incidence of 10.4–83 per million inhabitants per year.[1] These prevalence and incidence figures vary widely because of their relationship with local demographic and socioeconomic factors. Fifty percent of the patients with SCI are diagnosed as complete, and in one-third of the patients, the SCI is reported as tetraplegic.[1]

In tetraplegia, the arm and hand function is affected to varying degrees, depending on the level and severity of the injury. To predict self-care function in cervical SCI, motor level is superior to neurological level.[2] Impaired hand function typically results in reduced independence with respect to performance of the activities of daily living and limits participation in socioeconomic activities.[1,3–5] Studies have shown that improvement in upper extremity function is one of the greatest needs in patients with tetraplegia.[6,7]

Spontaneous recovery of motor function below the initial neurological level occurs in almost all SCI patients and depends on several factors.[8]

First, the completeness of the lesion.[8–10] In patients with a complete SCI, motor function return occurs mainly within the zone of partial preservation. The recovery in patients with incomplete lesions is more substantial, and highly variable compared with patients with complete lesions.[8]

Secondly, the initial strength of the partly denervated muscle is a significant predictor of motor recovery to useful strength (grade 3 or higher on the Medical Research Council (MRC) Motor Strength Scale).[9] Recovery in muscles with some voluntary function is both faster and more complete than in muscles that initially had no function.[8] In addition, rapid onset of strength recovery is a good predictor.[9]

Thirdly, there is some evidence that the motor grade of the functional level, which was initially classified as lowest, influences the probability of the return of function in the level below.[8,11] Approximately 70–80% of motor-complete

Correspondence: Dr MJA Jannink, Roessingh Research and Development, Roessingshsbleekweg 33b, Enschede 7522 AH, The Netherlands.
E-mail: m.jannink@rrd.nl
Received 25 March 2008; revised 4 July 2008; accepted 21 July 2008; published online 30 September 2008

tetraplegic patients with some motor strength (MRC motor score grade 1–2) in the zone of injury could recover to the next neurological level within 3–6 months, whereas only 30–40% of patients with no motor strength (MRC motor score grade 0) in the zone of injury would gain a level during the same period.[10]

The final factor influencing the rate of spontaneous recovery is the time since injury.[8–10] The vast majority of spontaneous recovery (77%) takes place in the first 3 months, with a small amount of further recovery up to 18 months and occasionally longer.[8]

To enhance function and independence after injury, intensive rehabilitation therapy for the upper extremities in tetraplegic patients is considered to be very important.[6,12,13] A cornerstone of rehabilitation is exercise therapy (ET). In this respect, ET was defined as a series of movements with the aim to improve the upper extremity motor control (that is, muscle strength or muscle grade) and functional ability (that is, activities of daily living).

The main objective of this review is to investigate the effects of ET on the upper extremity motor control and functional ability of SCI patients by means of a systematic analysis of the literature.

Methods

Literature search

This review is based on a systematic literature search of studies published from January 1964 to April 2007 in the databases of PubMed, the Cochrane Library, EMBASE, the Center for International Rehabilitation Research Information and Exchange (CIRRIE) and the National Rehabilitation Information Center for Independence (REHABDATA). The following keywords were used in this search: spinal cord injury, SCI, spinal cord lesion, quadriplegia, exercise, exercise therapy, rehabilitation therapy, motor recovery, motor power, muscle strengthening, recovery of function and upper extremity. This strategy was adjusted for searching the other databases. In addition to searching the databases, the references of relevant publications were checked.

Study selection

The initial selection of articles was based on title and abstract. Three reviewers (MGMK, GJS and MJAJ) independently selected and summarized the studies and scored their methodological quality. The reviewers met regularly to discuss their findings and decisions. In case of disagreement, consensus was reached by discussion.

To be selected for review, a study had to

(1) involve patients with a complete or incomplete cervical SCI;
(2) investigate ET, possibly compared with other therapies (that is, electrical stimulation, biofeedback);
(3) focus on upper extremity motor control (and possibly functional abilities);
(4) be a clinical trial or (randomized) controlled trial; and
(5) be reported in a full-length publication in a peer-reviewed journal.

Studies focusing on the application of ET for paraplegic patients or on the lower extremities were excluded. To enable the most complete review of the current literature, the search was not limited by the stages of rehabilitation.

Methodological quality judgement

To obtain insight into the methodological quality of the included trials, the study designs were classified according to Jovell and Navarro-Rubio[14] (Table 1).

Data extraction

The analysis of the contents of the selected studies was based on a structured diagram. By constructing this diagram, the general contents of the studies were scanned for:

(1) patient characteristics;
(2) intervention(s) implemented in the study;
(3) outcome measures for the evaluation of the effects; and
(4) conclusions based on the results.

The conclusions were considered to be positive if the change between pre- and post-treatment measurement was significant or if there was a significant difference between several groups as calculated by an appropriate statistical test for the research question and the data characteristics. Statistical significance was set at $P<0.05$.

Results

Selection of studies

The systematic literature search in PubMed resulted in the identification of 447 studies. Eight of these studies[15–22] fulfilled the selection criteria, and were included in the present review. Additional searches in the Cochrane Library, EMBASE, CIRRIE and REHABDATA databases, and checking the references of relevant publications, resulted in no further inclusions. An overview of the characteristics of the reviewed articles is presented in Table 2.

Methodological quality judgement

Seven[15–19,21,22] of the selected studies were small randomized controlled trials with at least a pre- and post-treatment measurement and a methodological score of III, according to Jovell and Navarro-Rubio.[14] One study[20] was classified as a

Table 1 Classification of study designs by Jovell and Navarro-Rubio (1995)[14]

Level	*Strength of evidence*	*Type of study design*
I	Good	Meta-analysis of RCTs
II		Large-sample RCTs
III	Good to fair	Small-sample RCTs
IV		Non-randomized controlled prospective trials
V		Non-randomized controlled retrospective trials
VI	Fair	Cohort studies
VII		Case–control studies
VIII	Poor	Non-controlled clinical series; descriptive studies
IX		Anecdotes or case reports

Abbreviation: RCT, randomized controlled trials.

Table 2 Study and patient characteristics of the eight selected studies on exercise therapy in cervical SCI rehabilitation

Study	*Design*	*Intervention groups*	*No. at the end of study*	*Time since injury mean (s.d.) or range*	*Age mean (s.d.) or range in years*	*Neurological level at baseline*
Seeger *et al.*[15]	RCT study with crossover design	FES-assisted ET ET	7	1.5–11.9 years	Range 22–46	C4–C6; Biceps or triceps partially denervated
Klose *et al.*[16]	RCT study	8 weeks biofeedback followed by 8 weeks ET 8 weeks biofeedback followed by 8 weeks NMS 8 weeks NMS followed by 8 weeks ET ET	10 10 9 10	At least 1 year	Range 18–45	C4–C6, incomplete
Klose *et al.*[17]	RCT study	ET and NMS ET, NMS and EMG-biofeedback	14 14	At least 1 year	26.4 (5.3) 24.3 (4.0)	C5–C7[a]
						C4/5/6 C/I
Kohlmeyer *et al.*[18]	RCT study	Conventional treatment (with ET) Electrical stimulation Biofeedback Electric stimulation and EMG biofeedback	10 10 13 11	3.0 (0.9) weeks 3.2 (0.8) weeks 2.8 (0.8) weeks 2.5 (1.0) weeks	43 (18) 32 (13) 38 (15) 42 (15)	2/7/1 6/10 1/6/3 6/10 1/8/4 6/13 1/6/4 7/11[b]
Needham-Shropshire *et al.*[19]	RCT study	NMS-assisted arm ergometry exercise 4 weeks NMS-assisted exercise followed by 4 weeks of voluntary arm crank exercise Voluntary arm crank exercise	12 (21 muscles) 11 (18 muscles) 11 (22 muscles)	6 years 9 years 4 years	24 22 24	Cervical lesion; AIS unknown[c]
Hicks *et al.*[21]	RCT study	ET, with 2 × /month education	11	7.7 (6.4) years	36.9 (11.4)	Tetraplegia: C4-T2 Paraplegia: T3-S1 AIS A–D
		Control: 2 × /month education	12	12.1 (7.3) years	43.2 (9.3)	Tetraplegia: C4-C7 Paraplegia: T7-L2 AIS A, C, D
Beekhuizen and Field-Fote[22]	RCT study	ET	5	Range 12–154 months	Range 37–63	1 × C5; AIS D 4 × C6; 1 × AIS C, 3 × AIS D
		ET with somatosensory stimulation	5	Range 12–43 months	Range 22–39	2 × C5; AIS C 2 × C6; AIS C, D 1 × C7; AIS D

Abbreviations: AIS, ASIA (American Spinal Injury Association) Impairment Scale; C/I, complete/incomplete; EMG, electromyography; ET, exercise therapy; FES, functional electric stimulation; MRC, Medical Research Council; NMS, neuromuscular stimulation; RCT, randomized controlled trials.

[a]At least some active contraction of biceps and deltoids in gravity-eliminated planes. No previous tendon transfers.

[b]At least a poor grade for anterior deltoid and/or biceps, a trace in radial wrist extensors and MRC motor score 0 or a trace in triceps and distal muscles.

[c]At least one partial innervated triceps with MRC motor score 1–3 and both biceps with MRC motor score 3–5.

Table 3 Training characteristics

Study	*Total duration of the training*	*Frequency*	*Duration of each training*	*Intensity of exercise therapy*	*Type of exercise therapy*
Seeger *et al.*[15]	3–6 months	3–5 × /week	15 min extended to 60 min within 4 weeks	Eight contractions per min, to its maximum potential	Isotonic exercise through full ROM
Klose *et al.*[16]	16 weeks	3 × /week	Unknown	Unknown	Upper extremity strengthening exercises, self-care, transfer skills, mat mobility and wheelchair skills training
Klose *et al.*[17]	12 weeks	3 × /week	45 min ET 30 min NMS 30 min EMGs myofeedback Total 75 or 105 min	Maximize the voluntary contraction of the muscles being trained	Aggressive exercise therapy
Kohlmeyer *et al.*[18]	5–6 weeks	5 × /week	20 min Group 4: both treatments 10 min	Unknown	Conventional treatment: passive ROM, orthotic intervention, strengthening of available muscles (with a dynamic wrist extension assist orthosis) by exercise and functional activities
Needham-Shropshire *et al.*[19]	8 weeks	3 × /week	4 × 5 min	Cycling at 60 RPM, without discomfort	Arm ergometry training by arm crank exercise
Hicks *et al.*[21]	9 months	2 × /week	90–120 min	Ergometry: 70% of HF_{max} Resistance training: 70–80% of 1 RM	Aerobic training (arm ergometry) and resistance circuit training
Beekhuizen and Field-Fote[22]	3 weeks	5 × /week	2 h	Subjects repeatedly performed one task at a time until fatigued. A 2- to 3-min rest break was allowed before the start of a new task within the same category	Massed practice focused on continuous repetitions of tasks in each of five categories: gross upper extremity movement, grip, grip with rotation, pinch, and pinch with rotation. The subject repeatedly performed the tasks within that block for 25 min before moving to the next block. Feedback only when performing task incorrectly

Abbreviations: ET, exercise therapy; EMG, electromyography; HF_{max}, maximal hearth frequency; NMS, neuromuscular stimulation; 1 RM, one repetition maximum; ROM, range of motion; RPM, rounds per minute.

non-controlled trial with a methodological score of IX. However, patient characteristics and intervention parameters in this study were unclear, and the results and conclusions were incomplete. Therefore, it was excluded from further analysis.

Intervention

In six studies,[15–19,22] ET was compared with a combination of ET and an additional therapy; three studies[16–18] compared ET with ET in combination with electromyographic feedback; and five studies[15,16,18,19,22] compared ET with ET in combination with various kinds of electrical stimulation. The additional electrical stimulation therapies consisted of somatosensory electrical stimulation of the median nerve,[22] neuromuscular stimulation[16,19] and electrical stimulation of partly innervated muscles.[15,18] One study[21] focused on the effects of ET in combination with patient education. Table 3 presents the training characteristics of ET in the selected studies.

Patients

The size of the experimental and control groups were comparable in the selected studies and ranged from 5[22] to 14.[17] In six studies,[15–19,22] the neurological level at baseline ranged from C4 to C7. The study of Hicks *et al.*[21] also included patients with paraplegia, but only the results of the patients with tetraplegia were taken into account in the present systematic review. The time since injury was at least 1 year in six studies.[15–17,19,21,22] Only the study of Kohlmeyer *et al.*[18] contained patients with acute SCI.

Outcome measures

A total of 17 outcome measures were identified across the seven included studies (Table 4). Five studies[16–18,21,22] assessed functional outcomes and all seven studies[15–19,21,22] assessed motor control. The functional tests consisted of four different outcome measures: self-feeding,[16–18] hygiene and dressing skills,[16,17] mobility[16] and upper extremity function.[22] Different outcome measures were used to assess

Table 4 Outcome parameters and conclusion

Study	*Outcome measurements*	*Significant changes in the outcome measurements*	*Authors' conclusions*
Seeger *et al.*[16]	At baseline, after 3 and 6 months of training (6 and 12 months for one patient). Maximum active and passive elbow ROM Maximum voluntary extension or flexion force measured by a force-measuring myometer[a] MRC score of three exercises (0–5 points scale)	Only a significant change in the maximum voluntary force, average improvement from 0.32 kg before training to 0.52 kg after FES-assisted training	A 0.2 kg strengthening represents a very small change clinically. Neither FES nor conventional exercise successfully improved the strength
Klose *et al.*[16]	At baseline, after 8 and 16 weeks of training. Blinded researcher. Manual muscle test scores of biceps, triceps, wrist extensors and wrist flexors (0–10 points scale by Trombly) Voluntary EMG activity of these muscles Self-care scores, items related to feeding, hygiene and dressing Mobility scores, tasks related to transfers, mat mobility and wheelchair skills	Significant improvement in repeated measures of manual muscle test score, self-care scores and mobility scores for all the groups	Although the results did not provide any evidence for superiority of any of the individual or combined therapies to provide functional improvements, a statistically difference was found across time for each of the functional outcome measures
Klose *et al.*[17]	Six weeks prior to the start, at baseline, after 6 and 12 weeks of training. Modified motor index (Manual muscle test, 0–4 points scale by Lucas and Ducker) in biceps, triceps, wrist flexors and extensors Functional activity score related to feeding, hygiene and dressing skills	Significant improvement in repeated measures of the functional activity score for both groups	The results do not support the routine use of biofeedback in the treatment of chronic SCI, but rather further stress the importance of exercise therapy for such injuries
Kohlmeyer *et al.*[18]	Pre- and post-test, blinded evaluator. Manual muscle strength wrist extensors, anterior deltoid and biceps (0–8 points scale) Function score on self-feeding abilities	All treatment groups showed a significant improvement in muscle grades and function score	All four treatment groups showed improvements. No treatment group was superior to the others. Biofeedback and electrical stimulation alone or in combination offer no advantages over conventional rehabilitation treatment of wrist extensors
Needham-Shropshire *et al.*[19]	Four weeks prior to the start, at the start and after 4 and 8 weeks of training. Voluntary muscle function in triceps (ASIA motor score, 0–5 points scale)	After 4 weeks: in group 1 in comparison with group 3, significant improvement in triceps muscle grades. After 8 weeks: patients in groups 1 and 2 had a significantly higher proportion of muscles improving one or more muscle grades than in group 3	NMS is a useful strengthening tool in chronic SCI
Hicks *et al.*[21]	At baseline, after 3, 6 and 9 months of exercise. Arm ergometry performance Muscle strength chest, biceps, anterior deltoid(1 RM test) QOL (stress, depression, physical self-concept, pain, perceived health, perceived QOL) Psychological well-being	The experimental group showed a significant improvement in submaximal arm ergometry power output and upper body muscle strength. They also reported significant gains in psychological well-being	A twice-weekly program of progressive exercise training is effective in increasing strength, arm ergometry performance QOL and psychological well-being. No effect of neurological level on the magnitude of strength change
Beekhuizen and Field-Fote[22]	Pre- and post-test. Maximal pinch grip force measured with MicroFET 4 digital dynamometer[b] Upper extremity function (Wolf Motor Function Test and Jebsen Hand Function Test) Motor-evoked potentials elicited through transcranial magnetic stimulation Motor threshold thenar muscles	Significant improvements in pinch grip strength and Wolf Motor Function Test with exercise therapy (massed practice) and sensory stimulation. Jebsen functional scores improvement in both groups	Massed practice may be an effective rehabilitative tool for improving strength and function improvement. This may be further enhanced by the addition of somatosensory stimulation

Abbreviations: ASIA, American Spinal Injury Association; EMG, electromyography; FES, functional electric stimulation; MRC, Medical Research Council; NMS, neuromuscular stimulation; QOL, quality of life; 1 RM, one repetition maximum; ROM, range of motion.
[a]Myometer; Penny & Giles Transducers Limited (Dorset, UK).
[b]MicroFET 4 digital dynamometer; Hoggan Health Industries (West Jordan, UT, USA).

motor control. In three studies, the muscle strength was assessed and in five studies the muscle grade. Other outcome measures were quality of life and psychological well-being,[21] arm ergometry performance,[21] motor-evoked potentials and motor thresholds of the thenar musculature[22] and the range of motion of the elbow.[15]

Content of studies

Six studies[16–19,21,22] reported short-term follow-up improvements in motor control or functional ability of the upper extremity as a result of ET, or ET in combination with electrical stimulation or biofeedback (Table 4). Kohlmeyer *et al.*[18] and the two studies of Klose *et al.*[16,17] compared ET, electrical stimulation and biofeedback. They reported no treatment group superior to any other. Hicks *et al.*[21] reported progressive ET, twice a week to be effective in increasing arm strength, arm ergometry, quality of life and psychological well-being. Beekhuizen and Field-Fote[22] concluded that ET is effective in improving strength, which may be further enhanced by the addition of somatosensory stimulation. Needham-Shropshire *et al.*[19] reported neuromuscular stimulation to be more beneficial in improving motor score in patients with a chronic SCI. Only Seeger *et al.*[15] reported no significant improvement in muscle strength after electrical stimulation or conventional exercise in patients with a chronic SCI. None of the studies measured long-term follow-up improvements.

Discussion

Improvement of the upper extremity function is one of the greatest needs in patients with tetraplegia.[6,7] Therefore, an intensive rehabilitation program is considered to be very important to optimize function and functional ability of the upper extremity in these patients.[7,12] Although ET constitutes a substantial part of the upper extremity rehabilitation in SCI patients, only a few controlled trials reported on its effectiveness. Nevertheless, clinical experience has shown that ET is important, for example, to prevent contract and useless hands.[23] Seven studies fulfilled the selection criteria, in which ET for the upper extremity was investigated in cervical SCI patients. In this systematic review, they were qualitatively analyzed to assess the effectiveness of ET.

Six studies[16–19,21,22] reported positive effects owing to ET, electrical stimulation or biofeedback. Three studies reported positive effects on muscle strength, three studies on muscle grade and four studies on the functional ability of the upper extremity. Five of these studies focused on the chronic stage of SCI. As most of the studies focused on chronic SCI, it is reasonable to presume functional ability and motor control would not change to a great extent without therapy. This is in accordance with the findings of Hicks *et al.*,[21] they reported no significant change in the upper extremity function in the control group of chronic SCI patients receiving education only.

A plausible explanation for motor function improvement in the chronic stage is reorganization of the brain and spinal cord.[22,24] In this respect, a distinction must be made between skill training and strength training. Skill training induces synaptogenesis, synaptic potentiation and the reorganization of movement representations within the motor cortex. Strength training alters spinal motoneuron excitability and induces synaptogenesis within the spinal cord.[24] All training experiences induce changes in spinal reflexes, which are dependent on the specific demands of the task.[24] Finally, functional activities can also be improved by learning and using compensatory strategies.[17]

In the acute stage of SCI, it is difficult to differentiate between spontaneous recovery and the effects of ET. However, it appears reasonable that the principles of maximizing the function of spared fibers and the reorganization of the brain and spinal cord, as mentioned for chronic SCI patients, also apply to acute SCI patients.

Although the quality of the studies was good to fair, a potential bias in these research findings is the small number of patients and the lack of control groups. Four studies did not include a control group and remarkable is that, three studies used the ET group as control group. Another potential bias is the great variety in outcome measures, which makes it difficult to compare the results between studies.

The exact characteristics (for example, content) of ET were not described in detail in every study. Also the intensity of ET is not clear in all cases and varies between the studies. Furthermore, the type of exercise differs between studies. This makes it difficult to compare ET between the studies, as different types of exercise will lead to dissimilar recovery. The incomplete description of ET makes it difficult to check whether ET is in accordance with the principles of training and the key variables of motor learning.

The three principles of training, namely overload, specificity and reversibility, are important. Overload states that for an effect of training to occur, a system or tissue must be challenged with an intensity, duration and frequency of exercise to which it is not adjusted. The principle of specificity indicates that the training effect is limited to the system and tissues involved in the activity.[25] Reversibility is a consequence of the overload principle, and indicates that the gains are quickly lost when the overload is removed. The most important variable affecting the learning of motor skills is the intensity of practice itself.[26] According to the intensity of practice, motivation also plays an important role in learning. If the level of motivation is too low, people may not be sufficiently motivated to practice at all, and no learning will occur. Information about performance, that is, feedback, is the single most important variable for motor learning. Augmented feedback (information in addition to intrinsic sensory feedback that comes from an external source to the person performing the skill)[27] appears to have several possible mechanisms for enhancing learning.[28] It acts as information, forms associations between movement parameters and the resulting action, can have a motivational role[29] and will also enhance the cortical changes associated with motor learning.[30] In addition to these independent variables affecting the learning of motor skills, the structure of practice is also important. Intensity, task specificity and goal-orientated practice are important principles of motor control.[31] Further studies should provide systematic information about these aspects.

Interesting technological innovations in rehabilitation could make it easier to control and report these variables. Virtual reality is a promising modality for the creation of favorable practice environments in neurorehabilitation.[32] By means of virtual reality in rehabilitation it is possible to focus on different key concepts of motor (re-)learning: repetitive practice, feedback about performance and motivation.[30] Advantages of the use of virtual reality is the ability to make tasks easier, less dangerous, more fun, more challenging and easier to learn because of the salient feedback that can be provided during practice.[30,32] Although the amount of practice is an important variable for motor learning, variations in direction, timing and speed are needed to optimize the development of skills. These variations can be controlled with virtual reality.[32] Moreover, humans can learn motor skills in a virtual environment and transfer the motor learning to the real world.[33]

In addition to virtual reality, robotics is intended to be an adjunctive tool to increase the intensity of therapy. By means of these devices, it is possible to support the arm (compensation of gravity). This facilitates arm movements that enable patients to perform more training repetitions.[34]

Conclusion

Although ET is a cornerstone in the treatment of upper extremity in patients with SCI, only a small number of clinical and randomized controlled trials were found in literature. Most of the studies reported a positive effect of ET on upper extremity motor control and functional abilities in SCI patients. As ET is effective in patients with SCI in the chronic stage, this might have implications for the follow-up and treatment of these patients. Future studies should be more specific in describing the characteristics of ET to verify ET is in accordance with the current standards for training and motor relearning.

References

1 Wyndaele M, Wyndaele JJ. Incidence, prevalence and epidemiology of spinal cord injury: what learns a worldwide literature survey? *Spinal Cord* 2006; **44**: 523–529.
2 Marino RJ, Rider-Foster D, Maissel G, Ditunno JF. Superiority of motor level over single neurological level in categorizing tetraplegia. *Paraplegia* 1995; **33**: 510–513.
3 Beekhuizen KS. New perspectives on improving upper extremity function after spinal cord injury. *J Neurol Phys Ther* 2005; **29**: 157–162.
4 Ditunno Jr JF, Cohen ME, Hauck WW, Jackson AB, Sipski ML. Recovery of upper-extremity strength in complete and incomplete tetraplegia: a multicenter study. *Arch Phys Med Rehabil* 2000; **81**: 389–393.
5 Harvey LA, Batty J, Jones R, Crosbie J. Hand function of C6 and C7 tetraplegics 1–16 years following injury. *Spinal Cord* 2001; **39**: 37–43.
6 Snoek GJ, IJzerman MJ, Hermens HJ, Maxwell D, Biering-Sorensen F. Survey of the needs of patients with spinal cord injury: impact and priority for improvement in hand function in tetraplegics. *Spinal Cord* 2004; **42**: 526–532.
7 Anderson KD. Targeting recovery: priorities of the spinal cord-injured population. *J Neurotrauma* 2004; **21**: 1371–1383.
8 Fawcett JW, Curt A, Steeves JD, Coleman WP, Tuszynski MH, Lammertse D *et al*. Guidelines for the conduct of clinical trials for spinal cord injury as developed by the ICCP panel: spontaneous recovery after spinal cord injury and statistical power needed for therapeutic clinical trials. *Spinal Cord* 2007; **45**: 190–205.
9 Ditunno JF, Flanders AE, Kirshblum S, Granziani V, Tessler A. Predicting outcome in traumatic spinal cord injury. In: Kirshblum S, Campagnolo, Delisa (eds). *Spinal Cord Medicine*. Lippincott Williams and Wilkins: Philadelphia, 2007, pp 108–122.
10 Ditunno Jr JF, Stover SL, Freed MM, Ahn JH. Motor recovery of the upper extremities in traumatic quadriplegia: a multicenter study. *Arch Phys Med Rehabil* 1992; **73**: 431–436.
11 Ditunno Jr JF. The John Stanley Coulter Lecture. Predicting recovery after spinal cord injury: a rehabilitation imperative. *Arch Phys Med Rehabil* 1999; **80**: 361–364.
12 Kirshblum S, Ho CH, House JG, Druin E, Nead C, Drastal S. Rehabilitation of spinal cord injury. In: Kirshblum S, Campagnolo, Delisa (eds). *Spinal Cord Medicine*. Lippincott Williams and Wilkins: Philadelphia, 2001, pp 275–298.
13 Murphy CP, Chuinard RG. Management of the upper extremity in traumatic tetraplegia. *Hand Clin* 1988; **4**: 201–209.
14 Jovell AJ, Navarro-Rubio MD. Evaluation of scientific evidence. *Med Clin (Barc)* 1995; **105**: 740–743.
15 Seeger BR, Law BM, Creswell JE, Stern LM, Potter G. Functional electrical stimulation for upper limb strengthening in traumatic quadriplegia. *Arch Phys Med Rehabil* 1989; **70**: 663–667.
16 Klose KJ, Schmidt DL, Needham BM, Brucker BS, Green BA, Ayyar DR. Rehabilitation therapy for patients with long-term spinal cord injuries. *Arch Phys Med Rehabil* 1990; **71**: 659–662.
17 Klose KJ, Needham BM, Schmidt D, Broton JG, Green BA. An assessment of the contribution of electromyographic biofeedback as an adjunct therapy in the physical training of spinal cord injured persons. *Arch Phys Med Rehabil* 1993; **74**: 453–456.
18 Kohlmeyer KM, Hill JP, Yarkony GM, Jaeger RJ. Electrical stimulation and biofeedback effect on recovery of tenodesis grasp: a controlled study. *Arch Phys Med Rehabil* 1996; **77**: 702–706.
19 Needham-Shropshire BM, Broton JG, Cameron TL, Klose KJ. Improved motor function in tetraplegics following neuromuscular stimulation-assisted arm ergometry. *J Spinal Cord Med* 1997; **20**: 49–55.
20 Schalow G. Recovery from spinal cord injury achieved by 3 months of coordination dynamic therapy. *Electromyogr Clin Neurophysiol* 2002; **42**: 367–376.
21 Hicks AL, Martin KA, Ditor DS, Latimer AE, Craven C, Bugaresti J *et al*. Long-term exercise training in persons with spinal cord injury: effects on strength, arm ergometry performance and psychological well-being. *Spinal Cord* 2003; **41**: 34–43.
22 Beekhuizen KS, Field-Fote EC. Massed practice versus massed practice with stimulation: effects on upper extremity function and cortical plasticity in individuals with incomplete cervical spinal cord injury. *Neurorehabil Neural Repair* 2005; **19**: 33–45.
23 Bedbrook G. *The Care and Management of Spinal Cord Injury*. Springer Verlag: New York, Heidelberg, Berlin, 1981.
24 Adkins DL, Boychuk J, Remple MS, Kleim JA. Motor training induces experience-specific patterns of plasticity across motor cortex and spinal cord. *J Appl Physiol* 2006; **101**: 1776–1782.
25 Powers SK, Howley ET (eds). The physiology of training: effect on VO2 max, performance, homeostasis, and strength. In: *Exercise Physiology, Theory and Application to Fitness and Performance*, 5 edn. McGraw-Hill: New York, 2004, pp 249–275.
26 Schmidt RA, Lee TD. Condition of practice. In: *Motor Control and Learning: A Behavioural Emphasis*, 4 edn. Human Kinetics: Champaign, IL, 2005.
27 Magill RA. Augmented feedback. In: *Motor Learning and Control: Concepts and Applications*, 7 edn. McGraw-Hill: New York, 2004.
28 van Dijk H, Jannink MJ, Hermens HJ. Effect of augmented feedback on motor function of the affected upper extremity in rehabilitation patients: a systematic review of randomized controlled trials. *J Rehabil Med* 2005; **37**: 202–211.

29 Schmidt RA, Lee TD. Augmented feedback. In: *Motor Control and Learning: A Behavioural Emphasis*, 4 edn. Human Kinetics: Champaign, IL, 2005.
30 Holden MK. Virtual environments for motor rehabilitation: review. *Cyberpsychol Behav* 2005; **8**: 187–211.
31 Hesse S, Schmidt H, Werner C, Bardeleben A. Upper and lower extremity robotic devices for rehabilitation and for studying motor control. *Curr Opin Neurol* 2003; **16**: 705–710.
32 Stewart JC, Yeh SC, Jung Y, Yoon H, Whitford M, Chen S-Y *et al*. Intervention to enhance skilled arm and hand movements after stroke: a feasibility study using a new virtual reality system. *J Neuroeng Rehabil* 2007; **4**: 21.
33 Standen PJ, Cromby JJ. Can students with developmental disability use virtual reality to learn skills which will transfer to the real world? Paper presented at the Virtual Reality and Persons with Disabilities Conference 1995, San Francisco, CA.
34 Jannink MJA, Prange GB, Stienen AHA, Van der Kooij H, Kruitbosch JM, IJzerman MJ *et al*. Reduction of muscle activity during repeated reach and retrieval with gravity compensation in stroke patients. *Proceedings of the 10th International Conference on Rehabilitation Robotics (ICORR)* June 13–15, 2007, Noordwijk aan Zee, the Netherlands, pp 472–476 (doi:10.1109/ICORR.2007.4428468).