Received: May 13, 2009 First revision: August 14, 2009 Accepted: November 3, 2009

(www.interscience.wiley.com) DOI: 10.1111/j.1525-1403.2009.00266.x

Comparison of Four Evaluation Approaches in Transcutaneous Electrical Nerve Stimulation Treatment in Two Incomplete Tetraplegic Subjects

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Introduction: In the present investigation, we applied the whole-hand transcutaneous electrical nerve stimulation (TENS) therapy to two incomplete tetraplegic subjects and assessed their progress with four evaluation methods.

Methods: Two spinal cord injured subjects with spastic upper extremities participated in the study. The TENS therapy was added to their regular treatment. The TENS was delivered to the subject's hands by a conductive glove. The therapy consisted of 20-min sessions each working day during a period of four weeks. The used assessment methods were: maximal force test, force tracking task, Jebsen-Taylor hand function test, and modified Ashworth scale.

Results: The results show increased finger muscle strength, improved motor control and hand function in both patients. The reduction of muscle tone, as assessed by the modified Ashworth scale, was observed in one subject.

Discussion: There was no correlation found between the Jebsen-Taylor test and the maximal force test or force tracking task in this investigation. Assessment methods are complementary to each other as each one adds new or more detailed information about level of impairment.

Conclusion: From the comparison of four evaluation methods, it is evident that different assessments and measurements should be used in order to get better picture of patient's upper extremity impairment.

Keywords: Force tracking task, hand, Jebsen-Taylor hand function test, muscle tone, TENS

Conflict of Interest: The authors reported no conflict of interest.

INTRODUCTION

Spinal cord injury (SCI) in cervical region can result in partial or total loss of sensory and motor functions in upper extremities. In clinical practice, therapists use different methods to assess the level of impairment and to monitor the progress of therapy. The information on hand function is gained indirectly through evaluating different functional tasks (1–4), measuring passive and active range of motion (2–4), and/or measuring grip strength (3,5). The measurement of grip strength is usually done by dynamometers which measure only maximal voluntary grip force. No information about submaximal force control is obtained in this way (5).

Tracking tasks were found most appropriate for assessing the sensorimotor control capabilities (6). For gaining information about the grip force control, force tracking tasks were used (7–11). During force tracking, subject has to track the target as closely as possible by voluntarily controlling force applied to a force sensor. The tracking error is used to evaluate the tracking capability. However, in the literature there is lack of studies comparing hand force tracking performance with clinical assessment. Instead, tracking performance of patients is usually compared with tracking of healthy subjects (8–10).

In addition to a loss of sensory and motor functions, individuals with SCI often experience symptoms of spasticity (12). Spasticity is a disordered sensory-motor control, resulting from upper motor neurone lesion, presenting as intermittent or sustained involuntary activation of muscles (13). In several studies the effect of electrical stimulation on reduction of spasticity and improvement of sensorimotor function was documented (14–19). An interesting approach was developed by Dimitrijević (17). They stimulated the whole hand by a glove electrode. The positive effects in the sensory and motor function, achieved by whole-hand transcutaneous

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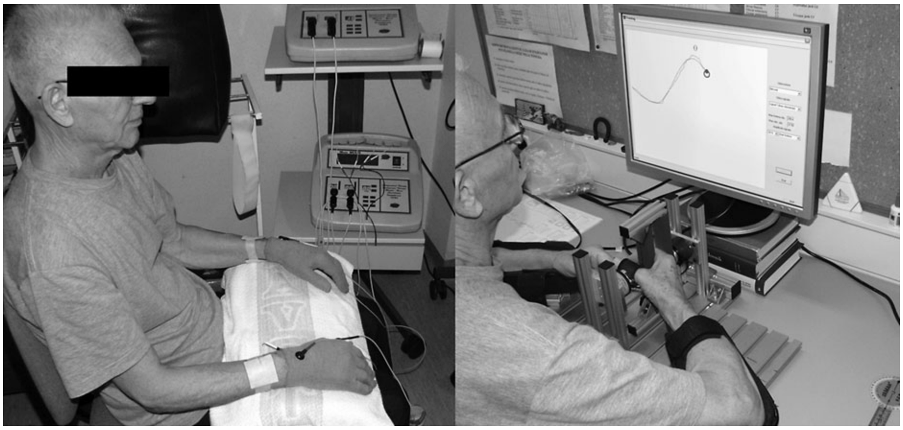

Figure 1. Subject during whole-hand electrical stimulation (left) and tracking task (right).

electrical nerve stimulation (TENS), were also reported by Peurala et al. (18).

In clinical practice the spasticity is usually evaluated by scales that assess muscle tone (muscle stiffness) such as the modified Ashworth scale (20,21). In experimental studies, force tracking tasks were also applied as evaluation tool in patients with spastic upper extremities (11,22). Kurillo et al. used isometric grip force tracking to evaluate Botolinum-Toxin treatment of spastic hand and showed improved tracking capability (11). McLellan et al. compared position and isometric force tracking and observed that pattern and location of the inappropriate activity in the spastic muscles was very similar in both tracking modes (22).

In our research, we applied glove stimulation of the hand in two patients with incomplete SCI who had spastic upper extremities according to clinical assessment. We assessed the progress in both patients by the maximal force test, force tracking task and with clinically established Jebsen-Taylor hand function test and modified Ashworth scale.

METHODS

Subjects

Two spinal cord injured subjects participated in the study. Subject GB was a 68-year-old man who was diagnosed incomplete tetraplegia due to intramedullary contusion at C5. Cause of the injury was fall with bicycle three months earlier. On the American spinal injury association (ASIA) impairment scale, he was categorized as an ASIA D. Subject MM was a 51-year-old man with incomplete tetraplegia as a result of a fracture at C2. Cause of his injury was fall from height, which happened four months earlier. Subject MM was categorized as an ASIA C. According to the clinical assessment, both subjects had more spastic left upper extremity in contrast to their right upper extremity. Prior to the electrical stimulation therapy, both subjects were informed of the procedures and gave informed consent to participate. Both subjects used the therapy in addition to their regular treatment at the rehabilitation institution. The study was approved by the ethics committee of Institute of Rehabilitation, Republic of Slovenia.

Stimulation protocol

Electrical stimulation was delivered to the subject's hand by commercially available conductive glove (Iskra Medical d.o.o., Ljubljana, Slovenia). The glove was connected to the stimulator as an anode, while two self-adhesive 50×50 mm electrodes were used as a common cathode. The electrical stimuli were monophasic current pulses delivered at 50 Hz with pulse width set at 200 µsec and pulse amplitude adjusted in the beginning of each treatment.

The whole-hand stimulation therapy lasted for four weeks. It was applied once a day for 20 min, five days per week. Before each treatment, the gloves were put on the hands and wetted with water. After that, the patient was seated in a comfortable position, with the arms relaxed on cushion in his lap (Fig. 1 left). The cathode electrodes were positioned approximately 2 cm from the glove, one on the dorsal and the other on the volar surface of the forehand. The stimulation intensity was set at the sensory threshold by adjusting the pulse amplitude and was kept constant through the treatment, but could differ from one treatment session to another.

Assessment protocol

The assessment of upper extremities abilities was divided into three phases: pre-therapy, therapy, and post-therapy phase. In the pre-therapy phase, only the maximal force test and the force tracking task were carried out during two successive days. The purpose of pre-therapy phase was to accustom subjects to the measuring system and to assess their initial maximal forces and tracking capabilities. In the therapy phase, the maximal force test and the force tracking task were carried out each day, while the Jebsen-Taylor hand function test and the modified Ashworth scale were carried out by experienced therapist in the beginning and at the end of each workweek. The post-therapy phase lasted for two days, in the week after the stimulation therapy completed. In both days, assessment with all four methods was carried out.

For the assessment of the maximal force test and force tracking task, our previously developed hand force measuring system was used (23). The hand force measuring device has two force sensors and enables the acquisition of isometric forces of extensor or flexor muscles of all five digits positioned in cylindrical grip. The finger force is calculated as sum of forces from both sensors. A PCI board is used for data acquisition from the force sensors. The data are sampled with a frequency of 100 Hz.

During the acquisition of maximal finger forces and during tracking task, the subject was seated behind the desk and his arm was placed into the hand force measuring device which was positioned on the desk in front of him (Fig. 1 right). The display providing the visual feedback was positioned in the eye level of the patient.

Maximal Force Test
In the maximal force test, the subject was asked to apply the highest possible force with his fingers to force measuring device. The maximal force of finger extensors and finger flexors was measured each day before the force tracking task.

Force Tracking Task
In force tracking test, the subject was asked to track the reference force as closely as possible by activating or releasing his finger forces of extensor or flexor muscles. The actual and the reference force were displayed on the monitor screen to provide visual feedback to the subject. The force reference signal was composed of four successive periods of the sinusoidal signal with frequencies of 0.05, 0.07, 0.10, and 0.20 Hz, respectively. The amplitude was adjusted to the 30% of the measured maximal force of the corresponding finger muscles.

The force tracking task was carried out twice for finger extensor and twice for finger flexors, except in the pre-therapy phase, when subjects performed the tracking task three times. In the therapy phase, both subjects completed the tracking task before stimulation, immediately after the stimulation and after 20-min rest. During the rest period, the subject was sitting in a chair and was requested to avoid any activities with the arms.

To assess the tracking performance, the relative root mean square error (rrmse) of tracking task was calculated. The tracking error was normalized by the amplitude of the reference signal to allow comparison of the results.

Jebsen-Taylor Hand Function Test
For hand function assessment, we used modified Jebsen-Taylor hand function test which comprises Jebsen-Taylor hand function test (1) and two additional subtests: labyrinth and screwing screw and nut. In the labyrinth subtest, the subject is required to track the labyrinth path printed on the paper with pencil without crossing the borders of the labyrinth. In the screw and nut subtest, the goal is to screw the nut on the screw as quickly as possible. All the subtests are timed by stopwatch. The assessment was always carried out before the electrical stimulation therapy.

Modified Ashworth Scale
The modified Ashworth scale (24) was used to assess muscle tone in finger flexor and extensor muscles. The scale has grades from 0 to 5, where grade 0 means no increase in muscle tone and grade 5 denotes rigid affected part. The assessment was carried out by the same therapist before the other measurements.

Statistical analysis

A statistical analysis was carried out using Spearman rank correlation to search for correlation between finger force-based assessment methods and clinical functional test. Data compared were results from Jebsen-Taylor hand function subtests and results from maximal force test and force tracking task, which were measured prior to TENS treatment the days that Jebsen-Taylor test was performed. Authors consider p values of 0.01 or less as statistically significant.

RESULTS

The results for left upper extremity of both subjects are presented in this section. The pre-therapy and post-therapy phases are in graphs

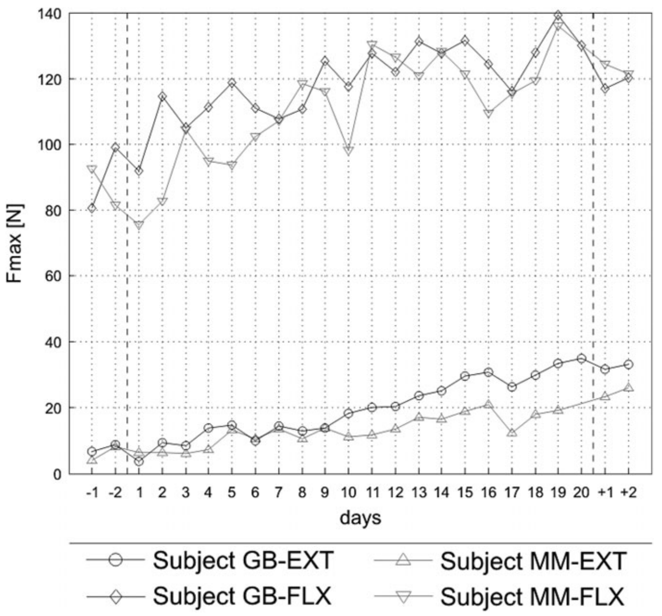

Figure 2. Maximal forces of finger extensors and finger flexors of both subjects throughout the assessment days. EXT, finger extensors; FLX, finger flexors.

separated from the therapy phase by a vertical dashed line and corresponding days are signed with minus and plus sign, respectively.

Maximal force test

Figure 2 shows the maximal finger forces for both subjects achieved throughout the assessment days. The results show improvement in both muscle groups, especially notable is progress in finger extensors. There is no significant difference observed in finger flexor forces between both patients. On the other hand, their finger extensor forces were in the beginning around the same level. However, in the second half of the assessment days, noticeable difference between their maximal finger forces can be seen.

Force tracking task

The tracking results of both patients are presented in Figure 3. The two left graphs represent the rrmse values of subject GB and the two right graphs show the rrmse values of subject MM. The tracking results for extensors are shown in the top two graphs and for finger flexors in the bottom two graphs. In the pre-therapy and post-therapy days, each bar represents average rrmse for that day. The three bars in the therapy phase represent the average rrmse before TENS, after TENS and after 20 min of rest, respectively. The trend of improvement in overall tracking performance is obvious in both subjects. However, the tracking performance after TENS and after the rest is different. After TENS, subject GB usually achieved better tracking, while tracking of subject MM was usually worse. Similar difference can also be observed after 20-min rest.

Jebsen-taylor hand function test

Figure 4 shows the results in all nine subtests of the Jebsen-Taylor hand function test for both subjects. In the days five and six for the screw and nut subtest, there are no data for subject MM as he was unable to complete the test. Both subjects show improvement in the hand function. Subject GB had in general better performance

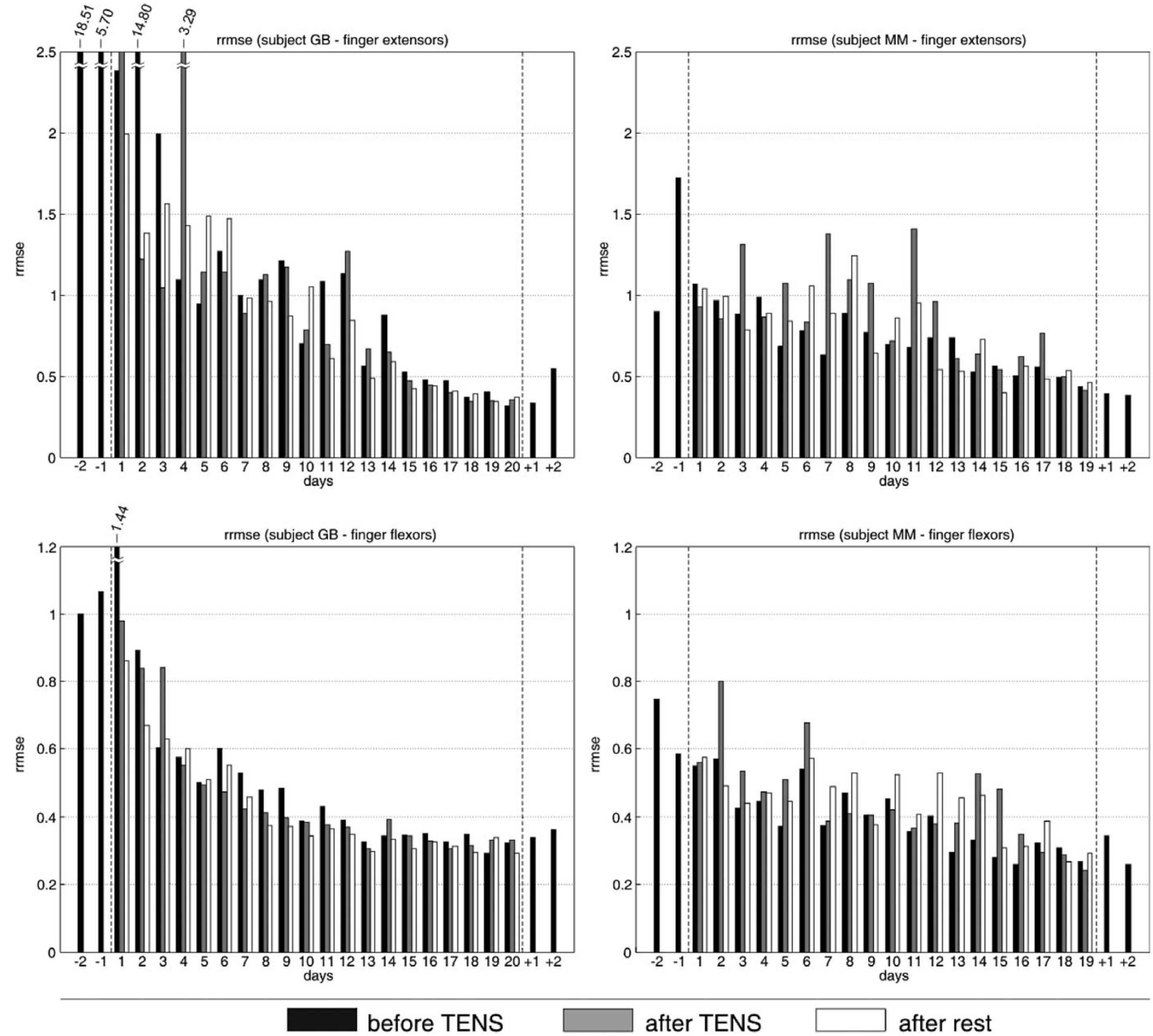

Figure 3. Force tracking error – relative root mean square error, for subject GB (top left: extensors, bottom left: flexors) and subject MM (top right: extensors, bottom right: flexors). TENS, transcutaneous electrical nerve stimulation.

than subject MM, who shows more variable and somewhat worse results.

Modified ashworth scale

Assessed muscle tone for both subjects according to the modified Ashworth scale is shown in Table 1. The reduction of muscle stiffness in both finger muscle groups is seen only in subject MM, while the grades for subject GB remained unchanged.

Statistical analysis

In Table 2, Spearman rank coefficients for Jebsen-Taylor hand function subtests and the maximal force test are presented. Subject GB has strong correlation in writing, labyrinth, turning cards, simulated feeding, and picking up large light objects for finger extensors and strong correlation in labyrinth subtest for finger flexors. Strong correlation for subject MM is found only for finger extensors in labyrinth and picking up large heavy objects subtests.

In Table 3, the Spearman rank coefficients for Jebsen-Taylor hand function subtests and the force tracking task are shown. The results in both patients show strong correlation with Labyrinth subtest. In the subject's MM tracking performance, there was no other strong relationship found between the two tests, while the subject GB had also high Spearman's ρ in checkers subtest.

DISCUSSION

In our investigation, we applied TENS to two patients with incomplete SCI. We assessed the progress of both patients by the maximal

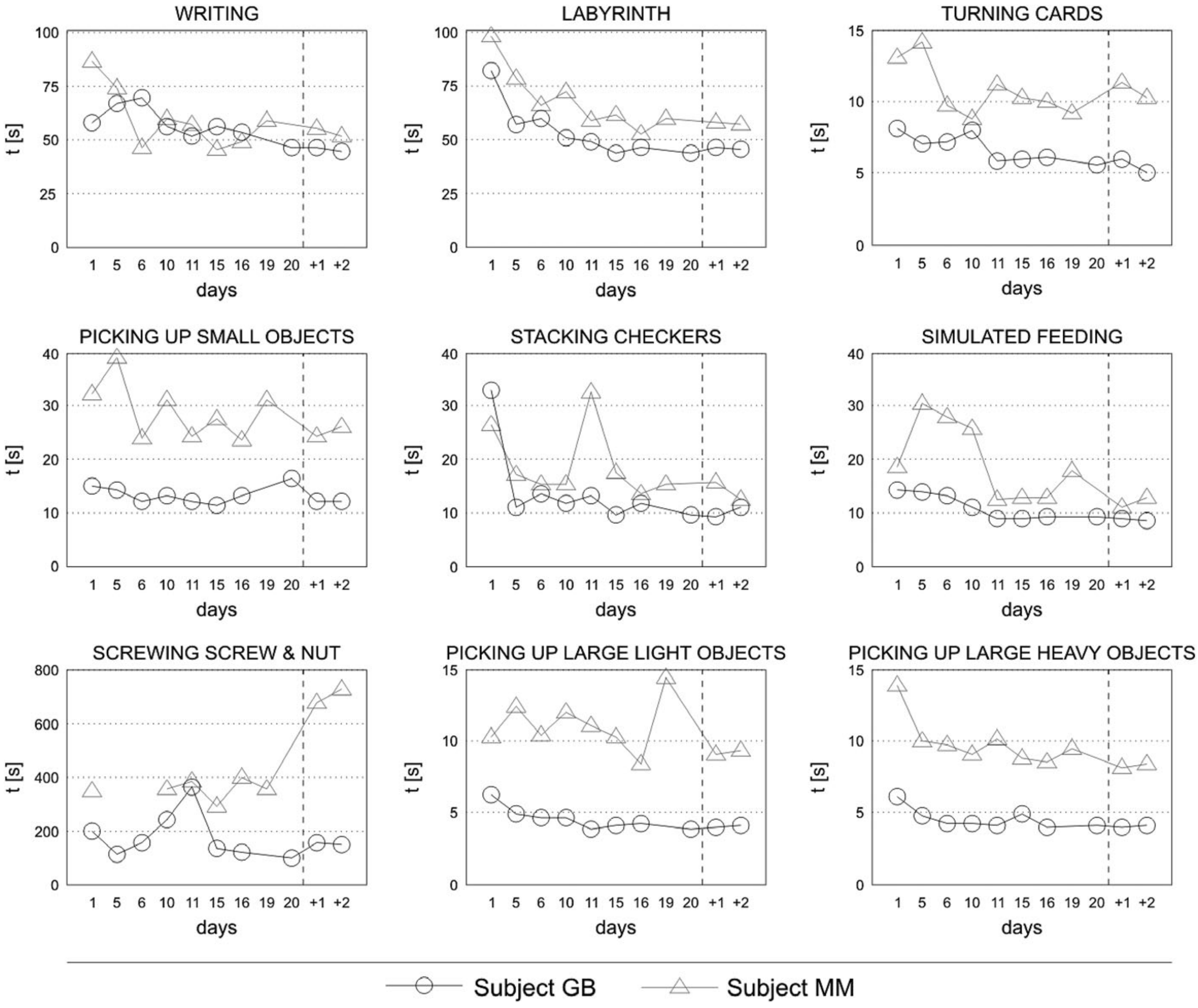

Figure 4. Results of the Jebsen-Taylor hand function test for both subjects.

Table 1. Muscle Tone in Finger Flexors and Extensors As Assessed by the Modified Ashworth Scale.

		First week	Second week	Third week	Fourth week	Post therapy
Subject MM	EXT	4, 4	4, 3	3, 3	3, 3	3, 3
	FLX	4, 4	4, 3	3, 3	3, 3	3, 3
Subject GB	EXT	0, 0	0, 0	0, 0	0, 0	0, 0
	FLX	2, 2	2, 2	2, 2	2, 2	2, 2

Two grades for each week: first grade—beginning of week, second grade—end of week.
EXT, finger extensors; FLX, finger flexors.

force test, the force tracking task, Jebsen-Taylor hand function test, and the modified Ashworth scale.

Throughout the four weeks of combined regular and TENS therapy, the evident increase in the maximal finger forces and tracking capability is observed. Both subjects achieved better tracking, i.e. lower rrmse, when tracking with finger flexors. This coincides with our previous experience, where healthy subjects also achieved better tracking with finger flexors than with finger extensors (23). Subject GB had very steady decline in the tracking error for finger flexors with no significant differences from day to day. His tracking with extensors was however, more instable. The tracking error varied greatly from day to day, except for last week. Similar inconsistency in tracking can be also observed in both muscle groups in subject MM. As the spasticity is a motor deficit, we assumed that the subject MM will achieve higher tracking error. It is interesting that he had in the beginning slightly better tracking performance than subject GB.

Table 2. Spearman Rank Coefficients for Jebsen-Taylor Hand Function Subtests and Maximal Finger Forces.

Subtest	Subject GB		Subject MM	
	EXT	FLX	EXT	FLX
Writing	ρ = −0.867*	ρ = −0.358	ρ = −0.382	ρ = −0.394
Labyrinth	ρ = −0.915*	ρ = −0.830*	ρ = −0.818*	ρ = −0.649
Turning cards	ρ = −0.867*	ρ = −0.649	ρ = −0.030	ρ = −0.236
Picking up small objects	ρ = −0.212	ρ = −0.139	ρ = −0.297	ρ = −0.430
Stacking checkers	ρ = −0.746	ρ = −0.479	ρ = −0.564	ρ = −0.103
Simulated feeding	ρ = −0.766*	ρ = −0.480	ρ = −0.612	ρ = −0.709
Screwing screw and nut	ρ = −0.491	ρ = −0.442	ρ = 0.810	ρ = 0.238
Picking up large light objects	ρ = −0.799*	ρ = −0.671	ρ = −0.467	ρ = −0.018
Picking up large heavy objects	ρ = −0.717	ρ = −0.249	ρ = −0.830*	ρ = −0.358

*$p < 0.01$.
EXT, finger extensors; FLX, finger flexors.

Table 3. Spearman Rank Coefficients for Jebsen-Taylor Hand Function Subtests and Tracking Task.

Subtest	Subject GB		Subject MM	
	EXT	FLX	EXT	FLX
Writing	ρ = 0.649	ρ = 0.685	ρ = 0.370	ρ = 0.467
Labyrinth	ρ = 0.855*	ρ = 0.903*	ρ = 0.830*	ρ = 0.842*
Turning cards	ρ = 0.600	ρ = 0.661	ρ = 0.091	ρ = 0.212
Picking up small objects	ρ = 0.152	ρ = 0.249	ρ = 0.309	ρ = 0.358
Stacking checkers	ρ = 0.867*	ρ = 0.855*	ρ = 0.515	ρ = 0.587
Simulated feeding	ρ = 0.565	ρ = 0.651	ρ = 0.697	ρ = 0.564
Screwing screw and nut	ρ = 0.624	ρ = 0.515	ρ = −0.762	ρ = −0.571
Picking up large light objects	ρ = 0.640	ρ = 0.750	ρ = 0.382	ρ = 0.382
Picking up large heavy objects	ρ = 0.681	ρ = 0.638	ρ = 0.782	ρ = 0.697

*$p < 0.01$.
EXT, finger extensors; FLX, finger flexors.

However, tracking of subject MM varied from day to day for both muscle groups, while the tracking of subject GB was inconsistent only with finger extensors. In study of McLellan et al. (22), coactivation of spastic flexors occurred when subjects were tracking with extensor muscles. If we compare the tracking results of one muscle group with the Ashworth grade of its antagonistic muscle group, we can state that inappropriate activity of spastic muscles could have interfered with the tracking, causing inconsistent tracking results from day to day. However, to confirm this assumption electromyographic (EMG) activity of muscles should have been measured. More consistent tracking is noticed for finger extensors for both subjects toward the end of the therapy days. From maximal finger forces in Figure 2, it is obvious that both subjects were also able to produce higher extensor forces. This could be due to increased muscle strength in finger extensors resulting from conventional therapy, and/or more selective finger extension without coactivation of the spastic finger flexors. Again, coactivation of spastic muscles could only be proved by EMG activity measurements.

The Jebsen-Taylor hand function test shows improvement in hand function in both subjects throughout the assessment days. It can be clearly seen that subject MM had reduced hand functionality as compared with the subject GB, what was also expected according to the modified Ashworth scale grades. In some subtests, significant differences can be observed between both subjects, which are not evident from the results of force tracking task and maximal force test. The Jebsen-Taylor test shows improvement in hand function while the tracking test shows improvement in motor control. However, there was no statistically significant correlation found between both tests, except for the labyrinth subtest in both subjects and stacking checkers subtest in subject GB. The labyrinth subtest is similar to the tracking task. It is the only subtest, where the path of the labyrinth is always the same and has similar role as reference tracking signal.

Based on results we can also say that no correlation was found between the Jebsen-Taylor test and the maximal force test. Statistically significant correlations vary for each subtest between both subjects and even between each muscle group of the same subject.

The authors expected correlation between both force tests and the Jebsen-Taylor subtests in which use of cylindrical grip is required (i.e. picking up heavy and light large objects). Strong and statistically significant correlation was found only in two cases for the maximal force test (see Table 2). Subject MM even has very weak correlation between picking up large light objects and both force tests. A very weak correlation is also observed in both subjects and both muscle groups between picking small objects subtest and both force tests. Picking small object requires use of two fingers, while in our force tests the fingers are positioned in cylindrical grip and all five fingers are used. In general correlation, results vary between both subjects and both muscle groups.

The improvement according to the modified Ashworth scale was observed in only one of the two subjects. It can be argued, whether this is due to the whole-hand TENS or the antispastic medicaments, that the subject was taking as part of regular treatment. In previous studies, long-term reduction of spasticity was observed when the stimulation therapy lasted for two or more weeks (16,18). If muscle tone would increase during the post-therapy days, we could claim with more certainty that the muscle stiffness reduction was due to the whole-hand stimulation.

Despite the evident improvement of both subjects, nothing concrete about effect of TENS on their recovery can be claimed. It seems that TENS had overall different effect on the tracking capability of both subjects. However, based on these results considering two subjects with incomplete tetraplegia in their sub-acute phase, no final conclusion about effect of TENS on tracking capability can be drawn. A better interpretation of the results could perhaps be possible if a series of baseline measurements would be carried out prior to the TENS therapy.

On the other hand, from comparison of results, it is evident that the assessment methods are complementary to each other. Each method adds new or more detailed information about level of impairment of upper extremity. From this aspect, the combination of assessment approaches is advised.

CONCLUSION

In our investigation, we applied the whole-hand TENS in two patients with incomplete SCI. We assessed the progress of both patients with the maximal force test, the force tracking task, the Jebsen-Taylor hand function test, and the modified Ashworth scale. From the comparison of the four methods used in this investigation, we can conclude that different assessment approaches should be combined to obtain better assessment of patient's upper extremity impairment.

Acknowledgements

The authors acknowledge the financial support from the Slovenian Research Agency (P2-0228, 3211-05000550). The authors would also like to thank both patients for participating in the study.

Authorship statements

Bajd, Perdan, Kamnik and Ceru designed the study. Munih provided equipment for data acquisition and was in charge of work supervision. Jelenc provided the equipment for TENS treatment. Ceru arranged patient recruitment for the study. Perdan and Ceru conducted the study, including data collection and data analysis. Bajd and Kamnik helped substantially with data analysis and interpretation of the data. Perdan and Kamnik prepared the manuscript, which was revised by Bajd, Ceru, Munih and Jelenc. All authors approved the final manuscript.

How to Cite this Article:

Perdan J., Kamnik R., Čeru B., Bajd T., Šavrin R., Jelenc J., Munih M. 2010. Comparison of Four Evaluation Approaches in Transcutaneous Electrical Nerve Stimulation Treatment in Two Incomplete Tetraplegic Subjects.
Neuromodulation 2010; 13: 238–245

REFERENCES

1. Jebsen RH, Taylor N, Trieschmann RB, Trotter MJ, Howard LA. An objective and standardized test of hand function. *Arch Phys Med Rehabil* 1969;50:311–319.
2. Carr JH, Shepherd RB, Nordholm L, Lynne D. Investigation of a new motor assessment scale for stroke patients. *Phys Ther* 1985;65:175–180.
3. McPhee SD. Functional hand evaluations: a review. *Am J Occup Ther* 1987;41:158–163.
4. Fugl-Meyer AR, Jääskö L, Leyman I, Olsson S, Steglind S. The post-stroke hemiplegic patient. I. A method for evaluation of physical performance. *Scand J Rehab Med* 1975;7:13–31.
5. Innes E. Handgrip strength testing: a review of the literature. *Aust Occup Ther J* 1999;46:120–140.
6. Jones RD. Measurement of sensory-motor control performance capacities. In: Bronzino JD, ed. *The biomedical engineering handbook*. Boca Raton: CRC Press, IEEE Press, 1995:2197–2218.
7. Kriz G, Hermsdörfer J, Marquardt C, Mai N. Feedback-based training of grip force control in patients with brain damage. *Arch Phys Med Rehabil* 1995;76:653–659.
8. Kunesch E, Schnitzler A, Tyercha C, Knecht S, Stelmach G. Altered force release control in Parkinson's disease. *Behav Brain Res* 1995;67:43–49.
9. Vaillancourt DE, Slifkin AB, Newell KM. Visual control of isometric force in Parkinson's disease. *Neuropsychologia* 2001;39:1410–1418.
10. Kurillo G, Zupan A, Bajd T. Force tracking system for the assessment of grip force control in patients with neuromuscular diseases. *Clin Biomech* 2004;19:1014–1021.
11. Kurillo G, Gregoric M, Goljar N, Bajd T. Grip force tracking system for assessment and rehabilitation of hand function. *Technol Health Care* 2005;13:1–13.
12. Adams MM, Hicks AL. Spasticity after spinal cord injury: a review. *Spinal Cord* 2005;43:577–586.
13. Burridge JH, Wood DE, Hermens HJ et al. Theoretical and methodological considerations in the measurement of spasticity. *Disabil Rehabil* 2005;27:69–80.
14. Dewald JPA, Given JD, Rymer WZ. Long-lasting reductions of spasticity induced by skin electrical stimulation. *IEEE Trans Rehabil Eng* 1996;4:231–242.
15. Daly J J, Byron Marsolais E, Mendell LM et al. Therapeutic neural effects of electrical stimulation. *IEEE Rrans Rehabil Eng* 1996;4:218–230.
16. Hummelsheim H, Maier-Loth ML, Eickhof C. The functional value of electrical muscle stimulation for the rehabilitation of the hand in stroke patients. *Scand J Rehab Med* 1997;29:3–10.
17. Dimitrijević MM. Mesh-glove. 1. A method for whole-hand electrical stimulation in upper motor neuron dysfunction. *Scand J Rehab Med* 1994;26:183–186.
18. Peurala SH, Pitkänen K, Sivenius J, Tarkka IM. Cutaneous electrical stimulation may enhance sensorimotor recovery in chronic stroke. *Clin Rehabil* 2002;16:709–716.
19. Yozbatiran N, Donmez B, Kayak N, Bozan O. Electrical stimulation of wrist and fingers for sensory and functional recovery in acute hemiplegia. *Clin Rehabil* 2006;20:4–11.
20. Platz T, Eickhof C, Nuyens G, Vuadens P. Clinical scales for the assessment of spasticity, associated phenomena, and function: a systematic review of the literature. *Disabil Rehabil* 2005;27:7–18.
21. Wood DE, Burridge JH, vanWijck FM et al. Biomedical approaches applied to the lower and upper limb for the measurement of spasticity: a systematic review of the literature. *Disabil Rehabil* 2005;27:19–32.
22. McLellan DL, Hassan N, Hodgson JA. Tracking tasks in the assessment of spasticity. In: Delwaide PJ, Young RR, eds. *Clinical neurophysiology in spasticity*. Amsterdam, New York, Oxford: Elsevier Science Publishers B. V., 1985:131–139.
23. Perdan J, Kamnik R, Obreza P, Kurillo G, Bajd T, Munih M. Design and evaluation of a functional electrical stimulation system for hand sensorimotor augmentation. *Neuromodulation* 2008;11:208–215.
24. Bohannon RW, Smith MB. Interrater reliability of a modified Ashworth scale of muscle spasticity. *Phys Ther* 1987;67:206–207.

COMMENTS

Spinal cord injuries are a frequent case of disability and result in total or partial obstruction of flow of both sensory and motor information that is instrumental for normal life. The resulting syndrome depends on the extent of direct injury of the cord or compression of the cord by displaced vertebrae or blood clots. In extreme cases trauma may lead to complete or partial transaction of the spinal cord. Tetraplegia refers to impairment or loss of motor and/or sensory function in the cervical segments of the spinal cord due to damage of neural elements within the spinal canal. Tetraplegia results in impairment of function in the arms as well as in the trunk, legs and pelvic organs. It does not include brachial plexus lesions or injury to peripheral nerves outside the neural canal.

Modern rehabilitation considers that the intensive treatment of tetraplegic patients will increase their level of recovery. The recovery of function occurs through the process of compensation, substitution, and dynamic reorganization. The repeated activities and activation of peripheral and central neural pathways with various agents (e.g., electrical stimulation) could lead to new types of integrated multiple sensory modalities, which directly affect the recovery. The primary objective of this type of rehabilitation is to train the neural system; thereby, promote "learning" by providing the substrate that without it would not be available.

Assessment is necessary to objectively estimate functional impairments and identify the biomechanical and neurophysiologic changes caused by the injury or disease. This facilitates essential customization of rehabilitation by providing the following: 1) identification of the "minimum muscle set" needed to provide functional movements; 2) identification of the output forces required to provide functional movements; and 3) assessment if the available muscles can generate the required muscle output. Perdan and colleagues in their paper "Comparison of four evaluation approaches in transcutaneous electrical nerve stimulation treatment in two incomplete tetraplegic subjects" demonstrate in a case study with two subjects that the assessment must be comprehensive and should combine clinical, psychological and objective measurable and verifiable tests in order to get the complete picture of the level of recovery.

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TENS therapy is an interesting and poorly understood approach, primarily used in the management of pain through the release of endorphins. The effect is thought to be explained by the gate-control theory proposed by Melzack and Wall in 1965 and by presynaptic inhibition in the dorsal horn of the spinal cord. The most recent Cochrane review[1] however failed to find conclusive evidence to support the treatment of acute pain. TENS has also been used to treat spasticity and beneficial effects were found in a sample of patients with spasticity associated with post-stroke hemiplegia[2]. The authors suggest that the underlying mechanisms may be due partly to an enhancement in presynaptic inhibition of the spastic reflexes and partly to a possible "disinhibition" of descending voluntary commands to the paretic motoneurons. The latter would support the possible effect on maximum voluntary force. Perdan's study is of course only with two subjects and does not attempt to present evidence for the effect of TENS on spasticity, pain or muscle strength. It does however demonstrate the complexity of mechanisms associated with recovery of function following central nervous system lesions and the importance of investigating changes in a range of impairments as well as at the activity level. Only through such approaches can we understand the mechanisms of natural recovery and the effect of interventions.

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REFERENCES

1. Nnoaham KE, Kumbang J Transcutaneous electrical nerve stimulation (TENS) for chronic pain Cochrane. *Database Syst Rev* 2008Jul 16;(3):CD003222.
2. Mindy F. Levin and Christina W.Y. Hui-Chan. Relief of hemiparetic spasticity by TENS is associated with improvement in reflex and voluntary motor functions *Electroencephaloography and Neurophysiology* April1992;84(2):131–142.

