Motor Control in Patients with Incomplete Spinal Cord Injuries and Various Voluntary Movement Capabilities

Shih-Wei Chou, MD, PhD; Yu-Cheng Pei, MD; Cheng-Hsiu Lai[1], PhD; Chia-Hua Kuo[2], PhD; Tieh-Cheng Fu, MD; Wei-Hsien Hong, PhD

Background: In this study, we attempted to verify the hypothesis that further improvements in volitional movement of patients with a spinal cord injury would diminish and ultimately suppress the segmental responses, while enhancing the supraspinal inhibitory influence.

Methods: Eleven patients with an incomplete spinal cord injury and partial preservation of motor function (ASIS grades C and D) were recruited. Their lower limbs were evaluated using polyelectromyography (PEMG) during voluntary movements, reinforcement maneuvers, tonic vibratory reflex, passive stretch reflex, irradiation of the passive stretch reflex (PSRirrad), and plantar reflex suppression.

Results: The reinforcement maneuver response, tonic vibratory response, passive stretch reflex, and PSRirrad were most active in limbs with partially preserved volitional movement, but for which patients were still incapable of lifting their heel off the examination table. In contrast, plantar reflex suppression was strongest in limbs with partially preserved volitional movement, for which patients were capable of lifting the heel off the examination table.

Conclusions: Supraspinal inhibitory effects were most active in those limbs which were capable of lifting the heel off the examination table, compared to limbs with partially preserved volitional activity but without visible movement or which were incapable of lifting the heel off the examination table. The capability for volitional activity paralleled the supraspinal inhibitory effects.
(Chang Gung Med J 2005;28:349-56)

Key words: motor control, spinal cord injury, stretch reflex, polyelectromyography.

The presence of brain excitatory and inhibitory influences has been demonstrated for neurological functions below the level of the spinal cord lesion in patients with clinically complete spinal cord injuries (SCIs).[1] Segmental responses, elicited by a reinforcement maneuver,[1] tonic vibratory reflex,[2,3] and passive stretch reflex[4] were shown in SCI patients using surface polyelectromyography (PEMG) in a Brain Motor Control Assessment (BMCA). In addition, plantar reflex suppression, which reflects preservation of the descending inhibitory influence, might respond in patients with clinically complete SCIs.[5]

Investigators' next step is to determine to what

From the Department of Physical Medicine and Rehabilitation, Chang Gung Memorial Hospital, [1]Department of Physical Education and Health, and [2]Laboratory of Exercise Biochemistry, Taipei Physical Education College, Taipei.
Received: Dec. 28, 2004; Accepted: Apr. 11, 2005
Address for requests: Dr. Shih-Wei Chou, Department of Physical Medicine and Rehabilitation, Chang Gung Memorial Hospital. 5, Fushing Street, Gueishan Shiang, Taoyuan, Taiwan 333, R.O.C. Tel.: 886-3-3281200 ext. 3846; Fax: 886-3-3274850; E-mail: f91033@cgmh.org.tw

extent residual motor control influences segmentally organized movement in patients with incomplete SCI, i.e., the relationship between the capability for residual motor control and organized movement in patients with incomplete SCI.

BMCA is a multi-channel PEMG technique, which provides a comprehensive assessment of motor control in spasticity.(6) BMCA has even been used to indicate descending control in apparently paralyzed subjects.(7,8) This method has been proven to provide objective, quantifiable, and reproducible assessments of SCI patients with different levels of motor control.(1)

In this work, we proposed that further improvements in the volitional movement of SCI patients would diminish and ultimately suppress the segmental responses, since suprasegmental control shares common segmental interneurons during the execution of such volitional movements. On the other hand, plantar reflex suppression was postulated to be positively correlated with improvements in volitional movement, since the supraspinal inhibitory influence parallels the capacity for volitional movement.

METHODS

Patients

Patients were selected from 99 patients with incomplete SCIs who had received a total of 162 standardized BMCA examinations. Incomplete SCI was determined using clinical neurological and BMCA examinations. Eleven patients, including 3 males and 8 females, whose first tests met the following inclusion criteria, were recruited. Their ages ranged from 23 to 67 (mean, 41) years. Lesion levels of the SCIs were between C4 and T10, and the time interval from the onset of injury to initiation of our study ranged from 3 to 178 (mean, 44) months. Informed consent was obtained from all patients in accordance with the principles of the Helsinki Declaration and with the approval of the Review Board for Human Research of Chang Gung Memorial Hospital.

Inclusion criteria were SCI patients with incomplete loss of motor function in the bilateral lower limbs (ASIA C or D) and spinal reflex activity preserved with normal lumbosacral evoked potentials (LSEPs).

Those who were taking anti-spastic medications or displayed significant comorbidities, such as pressure ulcers, active bladder infection, or an unstable medical condition, were excluded from this study.

Instrumentation

PEMG recordings (Astro-Med, West Warwick) were used to document motor control.(9) During the standardized sequence of the examination, the patient was placed in a comfortable supine position. Pairs of recessed, silver-silver chloride-surfaced electrodes were placed 3 cm apart over the midline of the muscle bellies of the quadriceps, hip adductors, hamstrings, tibialis anterior, and triceps surae muscles of each leg. The skin was prepared by lightly abrading it to obtain an electrode impedance of less than 5 kW for each electrode pair. PEMG channels were amplified using Grass 12A amplifiers with a gain of 5000 over a bandwidth of 40~600 Hz, digitized at 1800 samples per channel with 12-bit accuracy using the CODAS ADC (DATAQ Instruments, Akron, OH).

Procedures

Each patient received a series of examinations, including (1) a reinforcement maneuver, (2) voluntary movement, (3) tonic vibratory reflex, (4) passive stretch reflex, (5) irradiation of the passive stretch reflex (PSRirrad), and (6) plantar reflex suppression. During each examination, surface PEMG was concurrently recorded. The PEMG activities were then analyzed off-line to document the amplitude and pattern for each PEMG response.

(1) Reinforcement maneuver

Five different reinforcement maneuvers were tested. The first maneuver, a deep breath, was carried out by asking the patient to inhale quickly, hold the breath for the duration of a command tone, and finally, forcefully exhale. For the second maneuver, the patient was asked to tightly close his/her eyes during the tone. In the third, the patient clenched his/her jaw during the tone. The fourth, the patient was requested to lift his/her head, pressing against a pressure bag sensor by isolated neck flexion. For the fifth maneuver, the pressure sensor was placed between the palms and the patient vigorously pressed his/her hands together against the sensor (a modified Jendrassik maneuver). If paralysis of the upper extremities was such that the Jendrassik maneuver could not be carried out, a modified form employing forceful shrugging of the shoulders was used. Each reinforcement maneuver was held for 3 s in response to a command tone with a 3-s duration. Each maneuver was attempted 3 times with a 5-s inter-maneuver interval.

The existence of a reinforcement maneuver response was counted for each maneuver, indicated by a PEMG response occurring in at least 1 of the recorded muscle groups. A significant PEMG response was defined as PEMG activity of greater than 5 μV, which was elicited in at least 2 of the 3 attempts for each maneuver.

(2) Voluntary movements

Voluntary flexion of the bilateral hips and knees, followed by voluntary extension of the bilateral hips and knees, was attempted 3 times.

(3) Tonic vibratory reflex

A pneumatic vibrator was applied to elicit the tonic stretch reflex. The vibrator was placed over the patellar tendon and over the Achilles tendon, with the patient relaxed and lying in the supine position. Vibration was delivered for at least 30 s, while the PEMG responses were closely recorded.

For each limb, we respectively measured the effect of vibration on the patellar and Achilles tendons. Response activity was counted as being present if the activity was sustained with a tonic character and exceeded 20 μV.

(4) Passive stretch reflex

The passive stretch reflex was manually tested using the examiner's hands. The maneuver consisted of hip and knee flexion together (first phase) followed by extension (second phase). Each phase was maintained for a minimum of 5 s to ensure sufficient time for the subject's responses to plateau. The average amplitude of the greatest PEMG response among all recorded muscle groups was calculated. The response activity was counted as being present if the average amplitude exceeded 100 μV and was elicited in at least 2 of the 3 attempts.

(5) Irradiation of the passive stretch response (PSRirrad)

The PSRirrad was counted as occurring if a contralateral irradiation response was present during the passive stretch reflex.

(6) Plantar reflex suppression

This maneuver consists of stroking the plantar surface 3 times in a manner analogous to that used to elicit Babinski's sign, followed by 3 additional attempts. During each attempt, the patient was told that the stimulus had been given and was asked to voluntarily attempt to suppress the response by relaxing the limb.

The plantar reflex suppression was counted as being present for each individual limb if the response amplitude to the plantar stimulus was decreased by the suppression attempt and such inhibition occurred in at least 2 of the 3 attempts.

Data Analysis

The PEMG responses during volitional movements and reinforcement maneuvers were recorded for off-line analyses. The PEMG amplitude and pattern were analyzed. Based on voluntary movement capabilities, we divided the 22 studied limbs into the following 3 groups: (1) group 1, the no volitional movement group, with PEMG activity preserved but without visible volitional movement; (2) group 2, the partial volitional movement group, with partially preserved volitional movement but being incapable of lifting the heel off the examination table; and (3) group 3, the full volitional movement group, with volitional movement preserved and being capable of lifting the heel off the examination table.

Comparisons of the prevalence (number of positive responses/number of attempts) of each maneuver among the 3 study groups were analyzed descriptively. Differences in prevalences between the highest and lowest values exceeding 50% were taken as being obvious.

RESULTS

PEMG activity in volitional movement and reinforcement maneuvers

The 22 limbs studied were divided into 3 groups. Examples of PEMG responses during a reinforcement maneuver (neck flexion) and volitional movements are given in Figure 1. Group 1 was defined as having movement patterns with PEMG activity preserved but without visible volitional movement. At the same time, a lower amplitude of

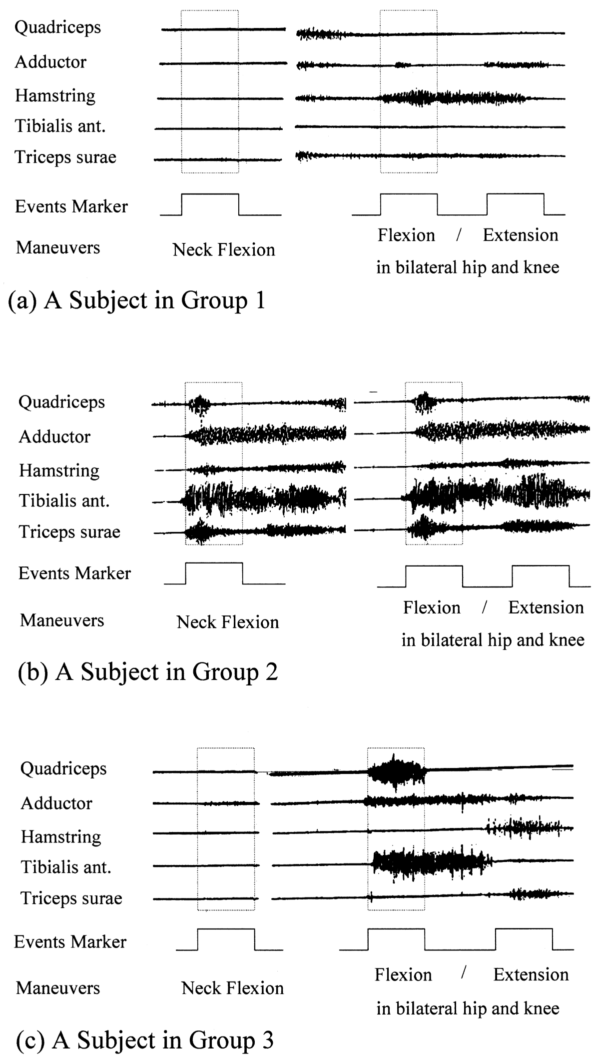

Fig. 1 PEMG activities and patterns in the 3 study groups, during neck flexion (1 of the reinforcement maneuvers) and volitional flexion/extension movements in the bilateral hips and knees. Group 1: the no volitional movement group, with PEMG activity preserved but without visible volitional movement. Group 2: the partial volitional movement group, with volitional movement partially preserved but being incapable of lifting the heel off the examination table. Group 3: the full volitional movement group, with volitional movement preserved and being capable of lifting the heel off the examination table.

PEMG activity during volitional movement and only traces of PEMG activity during the reinforcement maneuvers were displayed. However, the volitional movements and reinforcement maneuvers displayed distinctively different PEMG patterns. Group 2 was defined as having movement patterns with volitional movement preserved but being incapable of lifting the heel off the examination table. The volitional movements and reinforcement maneuvers displayed similar PEMG patterns. Group 3 was defined as having movement patterns with volitional movement preserved and being capable of lifting the heel off the examination table. The PEMG patterns illustrated volitional muscle contraction in each muscle. Different patterns between volitional movements and reinforcement maneuvers were demonstrated. Accordingly, 6, 8, and 8 limbs were assigned to groups 1, 2, and 3, respectively.

Tonic vibratory reflex

Table 1 demonstrates that the capability for voluntary movement was obviously dependent on the presence of the tonic vibratory reflex. The prevalence of the tonic vibratory reflex was highest in group 2, lower in group 3, and lowest in group 1.

Reinforcement maneuver

The capability for voluntary movement was not obviously dependent on the presence of the reinforcement maneuver response. The prevalence of the reinforcement maneuver responses was highest in group 2, lower in group 3, and lowest in group 1 (Table 1).

Table 1. Prevalence of Motor Control Features in Patients with Incomplete SCI

	Limbs	Prevalence (positive responses/attempts)				
	(n)	RMR	TVR	PSR	PSRirrad	PRS
Group 1	6	0.13	0.25	0.33	0.67	0.17
		(4/30)	(3/12)	(2/6)	(4/6)	(1/6)
Group 2	8	0.35	0.81	0.75	1.00	0.50
		(14/40)	(13/16)	(6/8)	(8/8)	(4/8)
Group 3	8	0.22	0.62	0.25	0.38	0.88
		(9/40)	(10/16)	(2/8)	(3/8)	(7/8)

Abbreviations: RMP: reinforcement maneuver response; TVR: tonic vibration reflex; PRS: plantar reflex suppression; PSRirrad: irradiation of the passive stretch reflex; PSR: passive stretch reflex.

Passive stretch reflex

Although the capability for voluntary movement was not found to be obviously dependent on the presence of the passive stretch reflex, the prevalence tended to be highest in group 2, lower in group 1, and lowest in group 3 (Table 1).

PSRirrad

The capability for voluntary movement was obviously dependent on the prevalence of the PSRirrad. The prevalence of the PSRirrad was highest in group 2, lower in group 1, and lowest in group 3 (Table 1).

Plantar reflex suppression

The prevalence of plantar reflex suppression progressively increased from group 1 to group 2 and then group 3, and was obviously associated with the capability for voluntary movement (Table 1).

DISCUSSION

Figure 2 demonstrates a postulated model of motor control in patients with incomplete SCI and different levels of voluntary control and SCI severity. Based on the capability for voluntary movement, we divided the 22 limbs studied into the following 3 groups: (1) group 1, the no volitional movement group, with PEMG activity preserved but without visible volitional movement; (2) group 2, the partial volitional movement group, with volitional movement partially preserved but being incapable of lifting the heel off the examination table; and (3) group 3, the full volitional movement group, with volitional movement preserved and being capable of lifting the heel off the examination table. In this model, nonspecific excitation by a supraspinal excitatory influence (a reinforcement maneuver response), supraspinal influence (a tonic vibratory response), and segmental activity (passive stretch reflex and PSRirrad) were most active in group 2, and less active in groups 1 and 3. In contrast, the supraspinal inhibitory influence (plantar reflex suppression) paralleled the capability for voluntary movement, which was highest in group 3 and lowest in group 1. In group 3, the absence or reduction of nonspecific excitation by the supraspinal excitatory influence, and of the supraspinal influence and segmental activity might reflect the increased supraspinal inhibitory effects, which was supported by an increase in the supraspinal inhibitory influence. In group 1, in contrast, the absence or reduction of nonspecific excitation by the supraspinal excitatory influence, and of the supraspinal influence, segmental activity, and also the supraspinal inhibitory influence might indicate substantial loss of descending control.

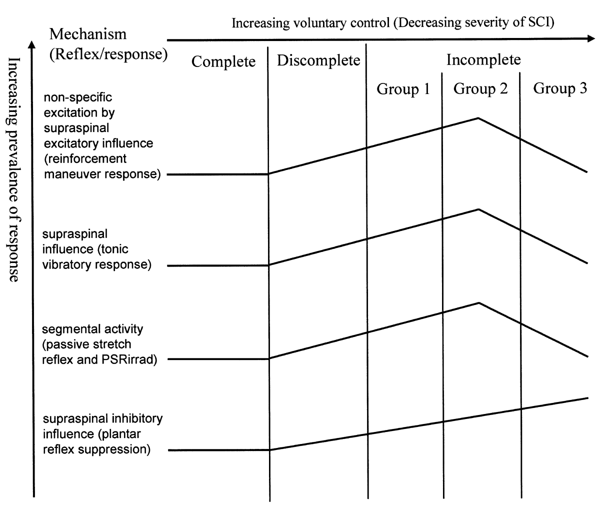

Fig. 2 Postulated model of motor control in patients with incomplete SCI and different levels of voluntary control and SCI severity. PSRirrad: irradiation of the passive stretch reflex. Incomplete: incomplete SCI was defined as neurophysiological measures revealing subclinical evidence of brain influence below the lesion although the lesions appeared to be clinically complete.[1]

Insufficient suprasegmental input in group 1 resulted in the trace PEMG response of the lower limbs during both specific voluntary and nonspecific reinforcement events. The fact that the PEMG patterns were similar between specific suprasegmental control (volitional movements) and nonspecific suprasegmental control (reinforcement maneuvers) in group 2 indicates that common segmental interneurons are shared by both events. Specific and nonspecific control systems are supposed to utilize a common pattern generator of the reorganized spinal cord to generate a similar PEMG pattern in specific and nonspecific controls. In contrast, the PEMG patterns in group 3 differed between the specific and nonspecific controls. This indicates that the limbs in group 3 could effectively utilize specific suprasegmental control rather than utilizing a common pattern generator. Powerful voluntary control in group 3 suppressed the nonspecific suprasegmental excitatory influence (e.g., the reinforcement maneuver response) and the suprasegmental influence on the segmentally organized reflex (e.g., the tonic vibration reflex).

Incomplete SCI is defined as neurophysiological measures revealing subclinical evidence of brain influence below the lesion, although the lesions appear to be clinically complete.(1) The tonic vibration response is dependent on suprasegmental input(10) and has been proven to be present in patients with incomplete SCI.(2,3) However, a tonic vibration response cannot be elicited in complete SCI, such as in subjects with complete division of the spinal cord.(11,12) Healthy subjects also demonstrated less of a tonic vibration response than SCI patients.(13) Hence, the tonic vibratory response follows a Gaussian distribution through the severity spectrum of SCI, with smaller responses in completely injured and uninjured patients.(14) Limbs in group 2 reflect intermediate SCI injury and, therefore, those values were scattered around the peak of distribution.

Segmental reflex activity elicited by passive stretch maneuvers also appears to follow a Gaussian distribution through the severity spectrum of SCI. The most-severe spasticity and the highest motor unit excitability in passive stretch maneuvers were found in non-ambulatory patients with incomplete SCI, compared to ambulatory patients with incomplete SCI or those with complete SCI.(4) Loss of suprasegmental input in group 1 and with residual suprasegmental inhibition in group 3 may account for the diminished segmentally organized responses (passive stretch reflex and PSRirrad). The descending influence on the segmental reflex was proven to be on the interneuron level, which then projects to motor neurons.(15,16) Limbs of group 2 had adequate suprasegmental influence converging on the intact segmental reflex arc and as a result, produced an exaggerated segmental reflex.

The ability to suppress the plantar reflex increased as volitional control increased with SCI. Preservation of descending control obviously exerts a suppressive effect on the plantar reflex in SCI patients.(5) Accordingly, impairment of motor control evidently results from removal of descending inhibition rather than from generation of descending facilitation.

In limbs with partially preserved volitional movement and which are capable of lifting the heel off the examination table, the absence or reduction of nonspecific excitation by supraspinal excitatory influence, and of supraspinal influence and segmental activity appears to reflect the increased supraspinal inhibitory effects, which were supported by an increase in the supraspinal inhibitory influence. In limbs with partially preserved volitional activity but without visible movement, the absence or reduction of nonspecific excitation by supraspinal excitatory influence, and of supraspinal influence, segmental activity, and also supraspinal inhibitory influence might indicate the substantial loss of descending control.

Acknowledgements

The authors would like to thank Milan R. Dimitrijevic, MD, DSc, Division of Restorative Neurology and Human Neurobiology, Baylor Medical College for his assistance in the laboratory design and critical review of this manuscript.

REFERENCES

1. Sherwood AM, Dimitrijevic MR, McKay WB. Evidence of subclinical brain influence in clinically complete spinal cord injury: discomplete SCI. J Neurol Sci 1992;110:90-8.
2. Dimitrijevic MR, Spencer WA, Trontelj JV, Dimitrijevic M. Reflex effects of vibration in patients with spinal cord lesions. Neurology 1977;27:1078-86.
3. Dimitrijevic MR, Faganel J, Lehmkuhl D, Sherwood A. Motor control in man after partial or complete spinal cord injury. In Desmedt JE, eds. Motor control mechanisms in health and disease. Advances in Neurology. New York: Raven Press, 1983;39:915-26.
4. Dimitrijevic MR. Spasticity and rigidity. In Jankovic J, Tolosa E, eds. Parkinson's disease and movement disorders. 3rd ed. Baltimore: Williams & Wilkins Co., 1998:159-75.
5. Cioni B, Dimitrijevic MR, McKay WB, Sherwood AM. Voluntary supraspinal suppression of spinal reflex activity in paralyzed muscles of spinal cord injury patients. Exp Neurol 1986;93:574-83.
6. Sherwood AM, McKay WB, Dimitrijevic MR. Motor control after spinal cord injury: assessment using surface EMG. Muscle Nerve 1996;19:966-79.
7. Dimitrijevic MR. Hsu CY, McKay WB Neurophysiological assessment of spinal cord and head injury. J Neurotrauma 1992;9(suppl 1):S293-300.
8. Sherwood AM, Priebe MM, Graves D. Consistency of multi-channel surface EMG recordings: application in spinal cord injured subjects. J Electromyogr Kinesiol 1997;7:97-111.
9. Sherwood AM, Dimitrijevic MR: Comprehensive assessment of control of motor activity: brain motor control assessment (BMCA). Phys Med Biol 1988; 33 (suppl): 163.

10. Matthews PB. The reflex excitation of the soleus muscle of the decerebrate cat caused by vibration applied to its tendon. J Physiol (Lond) 1966;184:450-72.
11. Burke D, Ashby P. Are spinal "presynaptic" inhibitory mechanisms suppressed in spasticity? J Neurol Sci 1972;15:321-6.
12. Ashby P, Verrier M, Lightfoot E. Segmental reflex pathways in spinal shock and spinal spasticity in man. J Neurol Neurosurg Psychiatr 1974;37:1352-60.
13. Sherwood AM, Dimitrijevic MR, McKay WB, Bacia T. Characteristics of the vibratory reflex in humans with reduced suprasegmental influence due to spinal cord injury. Restor Neurol Neurosci 1993;5:119-29.
14. Dimitrijevic MR, Dimitrijevic MM, McKay WB, Sherwood AM: Supraspinal influence on motor unit activity in paralyzed muscles: effects on reinforcement maneuvers. Arch Phys Med Rehabil 1981;62:540.
15. Lundberg A. Multisensory control of spinal reflex pathways. Prog Brain Res 1979;50:11-28.
16. Dimitrijevic MR, Faganel J. Motor control in the spinal cord. In: Eccles J, Dimitrijevic MR, eds. Recent achievements in restorative neurology 1: upper motor functions and dysfunctions. Basel: Karger, 1985;150-62.

具不同動作能力之不完全脊髓損傷病患之運動控制

周適偉 裴育晟 賴政秀[1] 郭家驊[2] 傅鐵城 洪維憲

背 景： 本實驗欲驗證的假說爲，當自主動作控制越好、中樞抑制調控能力增加，則脊髓損傷病患的不自主動作會大大降低。

方 法： 總共有十一位具有部份運動功能的脊髓不完全損傷的病患 (ASIA分類C與D級) 參與本實驗。受測者的下肢均以多電極表面肌電圖評估下列運動控制評估，包含有：自主動作、強化手法反應、張力振動反射、被動牽張反射與牽連式牽張反射、蹠反射抑制等。

結 果： 強化手法反應、張力振動反射、及被動牽張反射與牽連式牽張反射在具有自主活動能力但尚無力提起後跟的脊髓損傷病患中最爲活躍。相反的，蹠反射抑制則在可提起後跟之脊髓損傷病患中最爲顯著。

結 論： 中樞抑制調控能力，在可提起後跟的病患組比不能提起後跟的病患組要強的多。自主動作控制的能力與中樞抑制調控能力呈現一致性之相關。
(長庚醫誌 2005;28:349-56)

關鍵字：運動控制，脊髓損傷，牽張反射，表面肌電圖。

長庚紀念醫院 林口總院 復健科，[1]台北體育學院，[2]體育與健康學系 運動生化實驗室；長庚紀念醫院 台北院區
受文日期：民國93年12月28日；接受刊載：民國94年4月11日。
索取抽印本處：周適偉醫師，長庚紀念醫院 復健科。桃園縣333龜山鄉復興街5號。Tel.: (03) 3281200轉3846；Fax: (03) 3274850；E-mail: f91033@cgmh.org.tw