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Original Article

Temporal differences in relative phasing of gait initiation and first step length in patients with cervical and lumbosacral spinal cord injuries

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Study design: Comparison group design.

Objective: To compare the temporal distance factors during gait initiation between patients with incomplete cervical spinal cord injury, incomplete lumbosacral spinal lesion, and unimpaired control adults.

Setting: Human performance and movement analysis laboratory, Taiwan.

Participants: Five patients with an incomplete cervical spinal cord injury (Group 1), five patients with an incomplete lumbosacral spinal lesion (Group 2) and nine unimpaired control adults (Group 3).

Methods: Subjects underwent a three-dimensional gait analysis. The total gait initiation period, reaction time, each relative phasing of gait initiation and the length of the first step were identified by using the kinematic measurement system.

Main outcome measures: The total gait initiation period (start of the auditory cue for gait initiation to heel-strike of the first swing leg); each relative phasing of gait initiation indicated that the duration of the preparatory phase (start of auditory cue for gait initiation to heel-off of the first swing leg), the duration of the push-up phase (heel-off to toe-off of the first swing leg), and the duration of the single-stance phase (toe-off to heel-strike of the first swing leg) established by the total gait initiation period; and the length of the first step.

Results: The gait initiation period was greater in Groups 1 and 2 than that of Group 3 ($P < 0.05$). Each relative phasing including the duration of the preparatory phase, the push-up phase, and the swing phase relative to the total gait initiation period, did not differ among Groups 1–3 ($P > 0.05$). The length of the first step, measured while the nonpreferred leg stepped first in Groups 1 and 2, was shorter than that of Group 3 ($P < 0.05$).

Conclusions: Patients with incomplete cervical spinal cord injuries or lumbosacral spinal lesions took more time in gait initiation than unimpaired control adults. The first step length also reduced in these patients while the nonpreferred leg stepped first, as compared to unimpaired control adults. The data indicated that centrally programmed gait initiation might be preserved in ASIA-D spinal patients who, in this study, executed gait initiation with varying temporal distance strategies to compensate for peripheral impairments, as compared to unimpaired control adults.

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Introduction

The gait control process begins when appropriate afferent information is filtered from different sources. This information determines the organization of muscle synergies. Gait movements are then moderated to actual needs[1] through the interaction of this information with central programs. Different combinations of afferent inputs as well as the subsequent interaction of reflex

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mechanisms determine the correct programmed pattern[2] for locomotion. Correct pattern formation may also be determined by the instruction for a particular locomotion condition.[1,2]

A central pattern generator may drive the rhythmic lower extremity movement patterns shown during gait. This central generator is made up of a network of neurons intrinsic to the lumbosacral spinal cord,[3–5] and are regulated by supraspinal motor centers in the brain.[6–8] Trauma to the spinal cord and interruption of the spinal interneuronal circuits connecting the brainstem and the supraspinal motor center interfere with several aspects of normal gait.[1,2,6] Owing to resultant physical barriers, such as spasticity, muscle weakness, and abnormal proprioception, spinal patients are unable to bear their weight sufficiently on the affected lower limbs at the weight-bearing stance phase of the gait cycle, which leads to loss of balance and falls.[1,2,6,9,10] In recent studies,[6,8,10–13] it has been demonstrated that central pattern generator can be triggered in patients with complete or incomplete spinal cord injury (SCI) when the body is partially unloaded. Evidences include increased stride length and relative time span of the single-stance phase, and a reduction in the relative time span of the double-stance phase during the gait cycle.

Owing to their reduced reserves to support balance and gait, patients with incomplete SCI might adopt varying temporal distance strategies to achieve a safer, more stable gait pattern for an efficient control of dynamic balance during walking.[6,10]

Gait initiation challenges dynamic balance control because it is the transitional phase between static balance in an upright position and the start of steady-state walking. The analysis of temporal-distance strategies during gait initiation has provided important information about the coordination of posture and intentional movement in normal adults.[14–16] It has been found that the first step length, reaction time, the relative time span of single- and double-stance phases, propulsive forces, gait initiation speed, covariation of muscle activities, and sensory feedback are all vital components of generation of the appropriate gait initiation pattern.[9,16–25]

Problems with gait initiation performance may exaggerate locomotive deficiencies in the elderly[26–28] as well as neurologically impaired subjects, such as those suffering from Parkinson's disease[29–31] and stroke[32–34] and could be a sensitive indicator of balance dysfunction.[7,26,27,32,35,36] No studies investigate gait initiation deficiencies in the SCI population. Also, patients with lumbosacral spinal cord lesion may initiate gait differently from patients with high-level SCI. The differences may not only come from the varied areas of physical barriers between different levels of SCI but also from the influence of possible damaged central pattern generator[3–5,8] in patients with lumbosacral spinal cord lesion.

The purposes of this study are: (1) to compare temporal-distance strategies adopted during gait initiation among three groups: patients with cervical SCI, patients with lumbosacral injury, and unimpaired control adults; (2) to identify modification of temporal-distance strategies adopted during gait initiation in order to help us determine how the multivariable control is adjusted to impairments caused by SCI; and (3) to understand the modifications that SCI patients adopt to reduce the risk of falls. Gaining this understanding may thus enable further improvements to be made in rehabilitation design by working toward specific goals common to these patients.

Methods

Subjects
In all, 19 subjects were recruited for this study, including five patients with cervical SCI (Group 1, aged 20–47 years), five patients with lumbosacral spinal lesions (Group 2, aged 31–59 years), and nine unimpaired control adults (Group 3, aged 20–25 years). Sex, age, height, weight, body mass index (BMI), leg length, years after injury (chronicity), preferred leg, lower extremity ASIA motor, and sensory scores[37] were recorded for each subject (Table 1). Inclusion criteria for Groups 1 and 2 were: (1) class D of the ASIA impairment scale,[37] and a score of less than or equal to 1 in the lower extremity muscles as measured by the modified Ashworth scale was required for Group 1;[38] (2) a history of traumatic SCIS of more than 6 months; (3) the ability to walk more than 10 steps without any assistance or devices. Exclusion criteria for all three groups included any significant comorbid disease that would interfere with ambulation function. The experimental procedures were approved by the local institutional review board for human research and adhered to the Occupational Health and Safety administration regulations. Each subject gave their informed consent.

Instruments
A computerized, high-resolution three-dimensional motion analysis system (Vicon 370 suppliers: Vicon 370, Vicon motion system, 14, Minus Business Park, West Way, Oxford, OX2OJB, UK – six cameras, 60 Hz) was employed to obtain the temporal-distance parameters and the kinematic data during gait initiation in all subjects.

Procedures
Subjects stood barefoot, with 13 reflective markers placed on the sacrum and both sides of lower limbs at the anterior superior iliac spine (ASIS), lateral thigh, knee, lateral tibia, lateral malleolus, and the second metatarsal head. For the first trial, each subject was asked to step with their preferred leg first at a self-selected speed in response to an auditory cue. For the second trial, the SCI patients (Groups 1 and 2) were then asked to step with the nonpreferred leg first. Leg preference was defined as the leg chosen to kick an imaginary ball.[39,40] This was repeated twice with both

Table 1 Characteristics of Groups 1–3

	Sex (M/F)	Age (year)	Height (cm)	Weight (kg)	BMI (kg/M²)	Chronicity (year)	Leg length[a] (cm) (left/right)	Preferred leg (side)	Motor (L2-S1)[b]		Pinprick (L1-S4,5)[c]		Light tough (L1-S4,5)[c]	
									Left	Right	Right	Left	Right	Right
Group 1														
1	M	39	172	74	25.01	2.83	81/81	Right	20	19	18	16	18	16
2	M	33	173	56	18.71	10.91	81/81	Right	18	20	9	9	9	9
3	F	59	171	68	23.26	1	77/77	Left	20	20	12	12	12	12
4	M	31	177	63	20.11	0.83	86.5/85	Right	22	17	18	15	18	15
5	M	38	184	71	20.97	2.92	82/82	Left	20	20	9	9	9	9
Mean		40	175.4	66.4	21.61	3.7								
1SD		11.1	5.3	7.1	1.66	4.15								
Group 2														
1	M	47	170	62	21.45	1	87/71	Left	25	25	16	14	16	14
2	M	34	169	68	23.81	2.08	87/72	Right	25	25	15	15	15	15
3	M	20	154	51	21.5	2	87/73	Left	21	25	15	13	15	13
4	M	29	165	60	20.04	11	87/74	Right	25	23	16	15	16	15
5	M	24	164	52	19.33	5	87/75	Left	25	25	18	18	18	18
Mean		30.8	164.4	58.6	21.23	4.22								
1SD		10.5	6.4	7.3	1.72	4.08								
Group 3														
1	F	21	162	50	19.05		87/78	Left	25	25	18	18	18	18
2	F	25	152	50	21.64		87/79	Left	25	25	18	18	18	18
3	F	23	172	60	20.28		87/80	Left	25	25	18	18	18	18
4	F	22	166	55	19.96		87/81	Left	25	25	18	18	18	18
5	F	24	159	49	19.38		87/82	Right	25	25	18	18	18	18
6	F	24	161	51	19.68		87/83	Right	25	25	18	18	18	18
7	M	25	162	64	24.39		87/84	Left	25	25	18	18	18	18

[a]Leg length: anterior superior iliac spine to medial malleolous
[b]ASIA motor score summation from L2 to S1
[c]ASIA sensory score summation (pinprick or light tough) from L1 to S4-5

trials yielding the same results.[41] Data collection began with the participants standing steady for at least 5 s prior to applying the auditory cue. Subjects were allowed several practices before three formal data collection trials.

Data analysis

The total gait initiation period (TGIP) was defined as the interval from the start of gait initiation as the auditory cue began, to heel-strike of the first swing leg. The TGIP was divided into three subphases: Phase I (preparatory phase, start of the auditory cue to heel-off of the first swing leg) – the span of Phase I was recognized as the reaction time of the gait initiation;[24] Phase II (push-up phase, heel-off to toe-off of the first swing leg); and Phase III (single-stance phase, toe-off to heel-strike of the first swing leg). TGIP and Phases I, II, and III were identified by using the kinematic measurement system. Phases I, II, and III were normalized by the TGIP as relative phasing of gait initiation of individual subjects.[25] The first step length during TGIP was defined as the distance between the heels of the first stance leg and the first swing leg at the moment when the first swing leg contacted the ground. The first step length was also normalized by the lower-extremity length of each subject to exclude individual differences due to various lower-extremity lengths.

According to Table 1, leg preference is not related to lower-extremity ASIA motor and sensory scores across all three groups. Problems in motor control may be indicated by leg preference, with the preferred leg tending to be better than the nonpreferred leg in functional use.[40–42] Following neurological injury, leg sensitivity is quite considerable and leg preference is therefore very important for clinical rehabilitation purposes.[40] Therefore, in Groups 1 and 2, both the preferred leg and the nonpreferred leg were selected separately as the first swing leg, since the SCI pathology might be functional asymmetrically implicated in both legs,[41,42] and thus interfere with the entire gait initiation process. Only the preferred leg was used as the first swing leg in Group 3 given that unimpaired control adults initiate gait symmetrically, no matter which leg starts first.[9,32,40,42,43]

The Kruskal–Wallis one-way ANOVA by ranks test (K–W ANOVA) was carried out to compare the differences among the three groups with regard to TGIP, phase duration, and the first step length. A critical α-level of $P < 0.05$ was used throughout the study.

Results

The median and interquartile range (IQR) of the temporal distance variables with the preferred leg stepping first, and with the nonpreferred leg stepping first, is shown in Figures 1–6. The TGIP with the preferred leg leading was significantly longer in Groups 1 and 2 than in Group 3 ($P < 0.05$; Figure 1a). TGIP was 24.41% greater in Group 1 than in Group 2, 41.61% greater in Group 1 than in Group 3, and 13.83% greater in Group 2 than in Group 3. The TGIP with the nonpreferred leg leading was markedly more delayed in Groups 1 and 2 than in Group 3 ($P < 0.05$; Figure 1b). TGIP was 38.22% greater in Group 1 than in Group 2, 59.28% greater in Group 1 than in Group 3, and 15.24% greater in Group 2 than in Group 3 (Figure 1b). The reaction times (Figure 2) and the durations of Phase I (Figure 3), Phase II (Figure 4), and Phase III (Figure 5) did not reach significance ($P > 0.05$), no matter which leg stepped first. There was no significant difference in the first step length, with the preferred leg stepping first among the groups ($P > 0.05$; Figure 6a). However, the IQR value of the first step length in Group 2 (16.183% leg length) was higher than those in Group 1 (11.679%
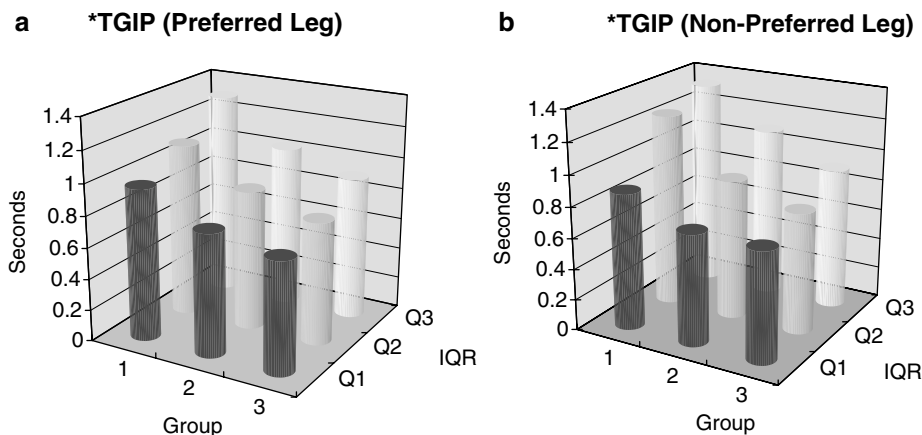

Figure 1 Median (Q2) and IQR (the first quartile Q1 to the third quartile Q3) of *total gait initiation period (TGIP)* while the preferred leg steps first (**a**) and while the nonpreferred leg steps first (**b**) in all three groups. The TGIP was the interval from the outset of gait initiation as the auditory cue began to the heel-strike of the first swing leg. TGIP unit: second. Group 1: patients with cervical SCI; Group 2: patients with lumbosacral spinal lesion; Group 3: normal adults. *P-value shows significant statistical differences across the three groups ($P < 0.05$)
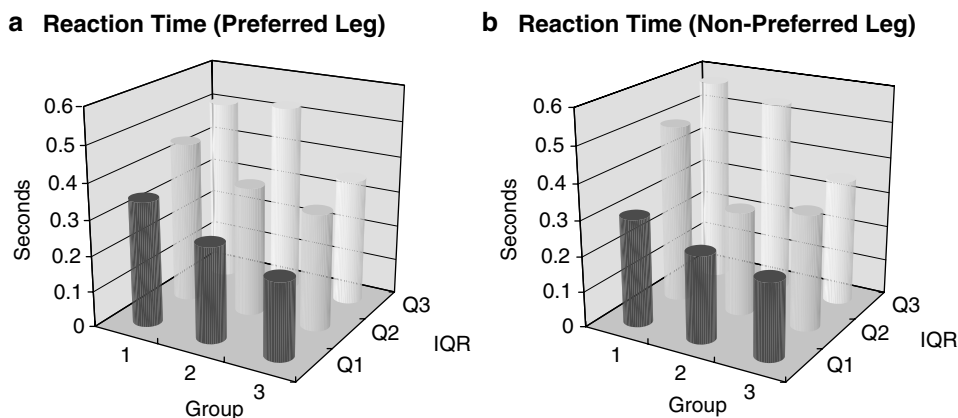
a Reaction Time (Preferred Leg)

b Reaction Time (Non-Preferred Leg)

Figure 2 Median (Q2) and IQR (the first quartile Q1 to the third quartile Q3) of *reaction time* while the preferred leg steps first (**a**) and while the nonpreferred leg steps first (**b**) in all 3 groups. Reaction time is the time interval between the auditory cue and the heel-off of the first swing leg. Reaction time unit: second. Group 1: patients with cervical SCI; Group 2: patients with lumbosacral spinal lesion; Group 3: normal adults
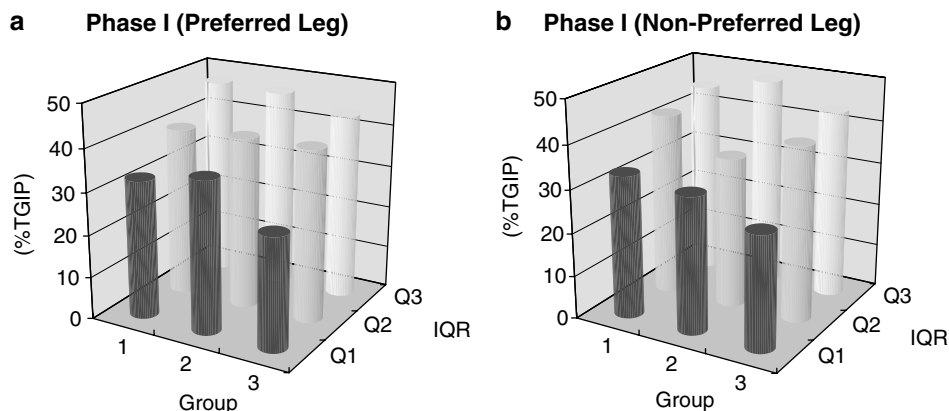
a Phase I (Preferred Leg)

b Phase I (Non-Preferred Leg)

Figure 3 Median (Q2) and IQR (the first quartile Q1 to the third quartile Q3) of *Phase I* while the preferred leg steps first (**a**) and while the nonpreferred leg steps first (**b**) in all three groups. Phase I is the preparatory phase, one of the relative phasings of gait initiation. Phase I is the duration from the start of gait initiation as the auditory cue began to heel-off of the first swing leg normalized by TGIP. Phase I unit: percentage of TGIP (%TGIP). Group 1: patients with cervical SCI; Group 2: patients with lumbosacral spinal lesion; Group 3: normal adults
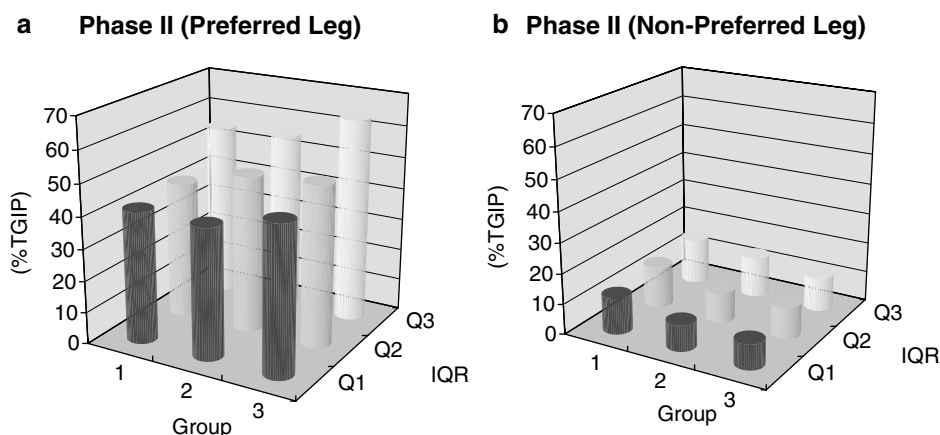
a Phase II (Preferred Leg)

b Phase II (Non-Preferred Leg)

Figure 4 Median (Q2) and IQR (the first quartile Q1 to the third quartile Q3) of *Phase II* while the preferred leg steps first (**a**) and while the nonpreferred leg steps first (**b**) in all three groups. Phase II is the push-up phase, one of the relative phasings of gait initiation. Phase II is the duration from heel-off to toe-off of the first swing leg normalized by TGIP. Phase II unit: percentage of TGIP (%TGIP). Group 1: patients with cervical SCI; Group 2: patients with lumbosacral spinal lesion; Group 3: normal adults
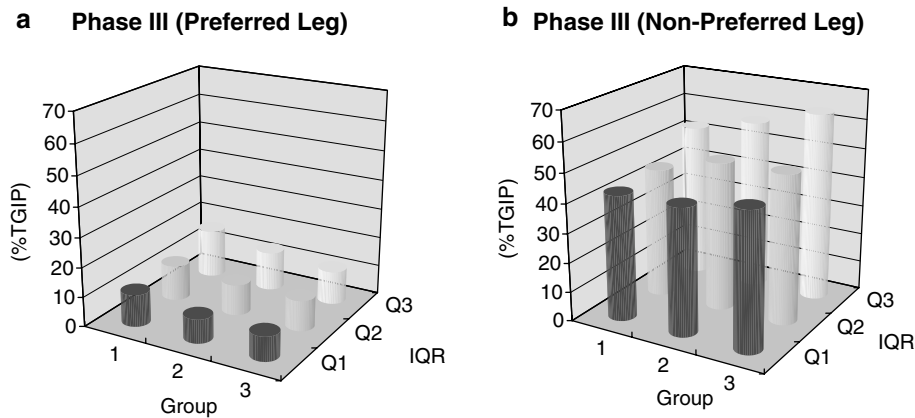
Figure 5 Median (Q2) and IQR (the first quartile Q1to the third quartile Q3) of *Phase III* while the preferred leg steps first (**a**) and while the nonpreferred leg steps first (**b**) in all three groups. Phase III is the single-stance phase, one of the relative phasings of gait initiation. Phase III is the duration from toe-off to heel-strike of the first swing leg normalized by TGIP. Phase III unit: percentage of TGIP (%TGIP). Group 1: patients with cervical SCI; Group 2: patients with lumbosacral spinal lesion; Group 3: normal adults
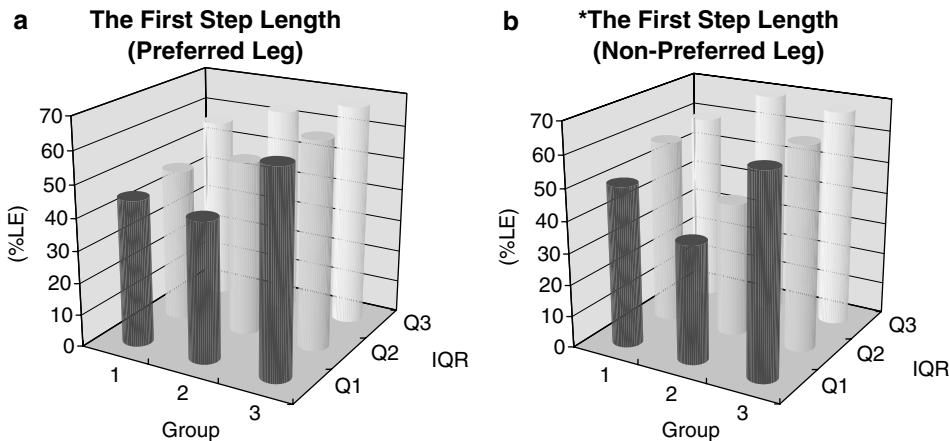

Figure 6 Median (Q2) and IQR (the first quartile Q1 to the third quartile Q3) of *the first step length* while the preferred leg steps first (**a**) and while the nonpreferred leg steps first (**b**) in all three groups. The first step length is the distance between the heels of the first stance leg and the first swing leg at the moment when the first swing leg contacted the ground normalized by the lower-extremity length. The First Step Length unit: Percentage of the lower extremity length (%LE length). Group 1: patients with cervical SCI; Group 2: patients with lumbosacral spinal lesion; Group 3: normal adults. *P-value shows significant statistical differences across the three groups ($P < 0.05$)

leg length) and Group 3 (5.119% leg length; Figure 6a). The first step length with the nonpreferred leg leading was significantly greater in Group 3 than in Groups 1 and 2 ($P < 0.05$; Figure 6b). The first step length was 36.65% greater in Group 1 than in Group 2, 10.74% greater in Group 3 than in Group 1, and 51.34% greater in Group 3 than in Group 2. The IQR value of the first step length in Group 2 (32.776% leg length) was higher than those in Group 1 (9.123% leg length) and Group 3 (5.119% leg length; Figure 6b).

Discussion

Total gait initiation period (TGIP)
Our results showed that patients with incomplete SCI took more time in gait initiation than unimpaired control adults (Figure 1). The results were in line with

the findings of various previous researches.[9,14,29,30,32] Proprioceptive disorders, muscle weakness, joint stiffness, pain, and fear of falling are all possible contributors to this phenomenon.[9,14,29,30,32] It revealed that impairment to the sensory and/or motor systems could delay the execution of gait initiation. Therefore, most of these neurogenic victims might adopt a less aggressive strategy for gait initiation. In addition, we found that lumbosacral spinal patients start their gait faster than cervical victims. Trunk instability, spasticity, and poor coordination of muscle activities may be related to the delay of gait initiation in high-level SCI patients.

Three subphases of gait initiation
The time-invariant central motor program includes characteristics such as invariant relative phasing limb movement and invariant submovement activation se-

quence.[25] The central programming in gait initiation is time invariant in many neurogenic disorders and normal control subjects.[25,26,29,30,39] This present study supports this conclusion. There was no statistical difference in the relative time span of the preparatory, push-up, and single-stance phases in gait initiation. Patients with cervical or lumbosacral SCI might execute a similar central motor programming for voluntary gait initiation, as did the unimpaired control adults.[32,36,44] Although the segmental spinal cord control in the patients of the two study groups was impaired, the central motor programming of gait initiation seemed to be mostly preserved in the ambulatory ASIA-D SCI cases. The unchanged relative time span of the preparatory, push-up, and single-stance phases, regardless of which leg stepped first, provide evident that during gait initiation, lower extremity movement pattern is alternative and rhythmic. It suggests that a central pattern generator may be activated because of gait initiation in the ambulatory ASIA-D SCI cases. The central pattern generator may also be preserved in ambulatory patients with lumbosacral spinal cord lesions. As a result of these studies, it is therefore possible that the central pattern generator in human beings is not necessarily located in the lumbosacral spinal cord area.[3–5]

Reaction time

Reaction time in gait initiation is the time interval between the auditory cue and the heel-off of the first swing leg.[24] In previous research, the reaction time in elders, children, and patients with Parkinson's disease has shown to increase significantly as compared with normal adults.[17,28,29,44] A slow gait initiation response may be attributed to degenerative changes and immaturity or pathologies of CNS. Thus, gait initiation might carry a high risk of falling when rapid stepping is carried out to increase the base of support and avoid hazard events.[28] However, the reaction time between the study and control groups did not reach significance, and our data suggest that SCI pathology in ambulatory ASIA-D SCI patients did not interfere with reaction time during gait initiation.

The first step length

Forward momentum generated by the first stance leg in the preparatory phase during gait initiation can determine the length of the first step.[9,19] The first step length in the hemiparetic subjects was longer when they stepped with the affected leg first instead of the nonaffected leg. The affected leg of hemiparetic patients had less weight-bearing ability than the normal leg. In this study, when the nonpreferred leg stepped first, the step length was significantly shorter in the study groups than in the unimpaired control groups. The preferred leg, as the first stance leg in the study groups, may have less weight-bearing ability and generated less forward momentum as compared to unimpaired control adults.

On the other hand, despite the trend that the IQR of the first step length in the unimpaired controlled group (62.934–68.053% leg length) was higher than those in the cervical SCI patients (45.284–56.963% leg length) and the lumbosacral SCI patients (47.372–63.555% leg length), the step length did not reach significance when the preferred leg stepped first (Figure 6a). The small case numbers in our study might account for the nonstatistical difference. However, both legs were affected due to SCI pathology, and leg preference might also lead to the discrepancy in the tolerance of body weight in term of dynamic stability.[9,32] This conclusion needs further investigation on the ground reaction force of the first stance leg during gait initiation, especially in the preparatory phase, to find out if leg preference influences the tolerance of body weight in the SCI patient population.

A high IQR value of the first step length was also found in lumbosacral spinal cases (Figure 6a and b). From a clinical point of view, patients with lumbosacral implications had high variations in the muscle strength of both lower limbs. This might result in asymmetry in the propulsive force generated in the preparatory phase and foot clearance during the single-stance phase of gait initiation. Therefore, their first step length varied because of the need for compensated hip and knee movements.

Gait versus gait initiation analysis

The characteristics of gait patterns in neurogenic patients include shortened step length, a lengthened gait cycle, and a shortened relative time span of single-stance phase.[10,29] The shortened relative time span of single-stance phase during the gait cycle is due to decreasing weight-bearing ability in the affected leg as the other leg takes a step forward. Prior studies have shown that gait training with partial body weight support may increase the step length and the relative time span of the single-stance phase in SCI patients with various levels implicated. In this study, we found that SCI and ASIS-D patients had lengthened gait initiation period, without a shortened relative time span of the single-stance phase of gait initiation despite which leg stepped first. However, a shortened first step length while the nonpreferred leg stepped first was noted. The results indicate that during gait initiation, the nonpreferred leg in our study subjects may have no difficulty in weight bearing in the single-stance phase, instead of a lengthened gait initiation period. A shortened first step length while the nonpreferred leg stepped first is, however, common in SCI and ASIS-D patients. The forward momentum generated by the first stance leg during the preparatory phase of gait initiation can determine the first step length.[9,19] Therefore, these patients may have difficulty in weight bearing and generating forward momentum of the preferred leg in the preparatory phase. From this point of view, we suggest that relearning the preferred leg's weight-bearing ability, especially in the preparatory phase of gait

initiation, should be added to ambulatory strategies. Thus, those who cannot tolerate a few steps of walking or who tend to be easily fatigued after walking a certain distance, might benefit from this task retraining.

Limitations of the study

Our patients who had ASIA-D SCI could walk independently more than 10 steps. The data in our study could not be applied to patients with SCI other than ASIA-D who rely on assistive devices to walk. Also, maximum hip and ankle angles and force measurements before toe-off of the swing limb during gait initiation were different between male and female subjects.[14,45] In our study, most of the study group patients were male (M:F = 9:1) and most of our normal control group adults were female (M:F = 2:7). This may partly explain the high variations of task performance in our subjects.

Conclusion

All three unchanged relative phasing of the gait initiation process indicated that centrally programmed gait initiation was preserved in the SCI ASIA-D patients. This study also demonstrated dissimilarity in first step length, which may be due to asymmetry in spinal implications. Given that the SCI patients had difficulty in generating forward momentum in the preparatory phase, there should be a greater emphasis on relearning weight bearing in the preparatory phase of gait initiation, to enhance/strengthen walking ability after SCI.

Acknowledgements

References

1 Dietz V. Physiology of human gait neural processes. In: Ruzicka E, Hallett M, Jankovic J (eds.) *Advances in Neurology (Vol. 87): Gait Disorders*. Lippincott Williams & Wilkins: Philadelphia, 1999, pp 53–63.

2 Berger W. Normal and impaired development of gait. In: Ruzicka E, Hallett M, Jankovic J (eds.) *Advances in Neurology (Vol. 87): Gait Disorders*. Lippincott Williams & Wilkins: Philadelphia, 1999, pp 65–70.

3 Chandler SH, Bakker LL, Goldberg LJ. Characterization of synaptic potentials in hindlimb extensor motoneurons during L-DOPA-induced fictive locomotion in acute and chronic spinal cats. *Brain Res* 1984; **303:** 91–100.

4 Fleshman JW, Lev-Tov A, Bruke RE. Peripheral and central control of flexor digitorum longus and flexor hallucis longus motoneurons: the synaptic basis of functional diversity. *Exp Brain Res* 1984; **54:** 133–149.

5 Floeter MK, Sholomenko GN, Gossard J-P, Burke RE. Dysnaptic excitation from the medial longitudinal fasciculus to lumbosacral motoneurons: modulation by repetitive activation, descending pathways, and locomotion. *Exp Brain Res* 1993; **92:** 407–419.

6 Dietz V, Wirz M, Jensen L. Locomotion in patients with spinal cord injury. *Phys Ther* 1997; **77:** 508–516.

7 Garcia RK, Nelson AJ, Ling W, Van Olden C. Comparing stepping-in place and gait ability in adults with and without hemiplegia. *Arch Phys Med Rehabil* 2001; **82:** 36–42.

8 Calancie B, Needham-Shropshire B, Jocobs P, Willer K, Zych G, Green BA. Involuntary stepping after chronic spinal cord injury: evidence for a central rhythm generator for locomotion in man. *Brain* 1994; **117:** 1143–1159.

9 Viton JM, Timsit M, Mesure S, Massion J, Franceschi JP, Delarque A. Asymmetry of gait initiation in patients with unilateral knee arthritis. *Arch Phys Med Rehabil* 2000; **81:** 194–200.

10 Visintin M, Barbeau H. The effects of body weight support on the locomotor pattern of spastic paretic patients. *Can J Neurol Sci* 1989; **16:** 315–325.

11 Finch L, Barbeau H, Arsenault B. Influence of body weight support on normal human gait: development of a gait retraining strategy. *Phys Ther* 1991; **71:** 842–856.

12 Wernig A, Muller S, Nanassy A, Cagol E. Laufband therapy based on 'Rules of Spinal Locomotion' is effective in spinal cord injured persons. *Eur J Neurosci* 1995; **7:** 823–829.

13 Visintin M, Barbeau H. The effects of parallel bars, body weight support and speed on the modulation of the locomotor pattern of psastic paretic gait. A preliminary communication. *Paraplegia* 1994; **32:** 540–553.

14 Brunt D, Lafferty MJ, Mckeon A, Goode B, Mulhausen C, Pole P. Invariant characteristics of gait initiation. *Am J Phys Med Rehabil* 1991; **70:** 206–212.

15 Das P, McCollum G. Invariant structure in locomotion. *Neuroscience* 1988; **25:** 1023–1034.

16 Crenna P, Frigo C. A motor programme for the initiation of forward-oriented movements in humans. *J Physiology* 1991; **437:** 635–653.

17 Winter DA. *A.B.C. (Anatomy, Biomechanics and Control) of Balance during Standing and Walking*. Waterloo Biomechanics: Waterloo, Canada, 1995.

18 Elble RJ, Moody C, Leffler K, Sinha R. The initiation of normal walking. *Mov Disord* 1994; **9:** 139–146.

19 Breniere Y, Do MC. Control of gait initiation. *J Mot Behav* 1991; **23:** 235–240.

20 Breniere Y, Dietrich G. Heel-off perturbation during gait initiation: biomechanical analysis using triaxial accelerometry and a force plate. *J Biomechanics* 1992; **25:** 121–127.

21 Breniere Y, Do MC. When and how does steady state gait movement induced from upright posture begin? *J Biomech* 1986; **19:** 1035–1040.

22 Herman R, Cook T, Cozzens B, Freedman W. Control of postural reactions in man: the initiation of gait. In: Stein RS, Pearson KG, Smith RS, Redford JB (eds.) *Control of Posture and Locomotion*. Plenum Press: New York, 1973, pp 363–388.

23 Kessler RM. The ankle and hindfoot. In: Kessler RM, Hertling L (eds.) *Management of Common Musculoskeletal Disorder*. Harper & Row: Philadelphia, 1983, pp 448–503.

24 Schmidt RA, Lee TD. Methodology for studying motor performance (Chapter 2). In: *Motor Control and Learning: A behavioral Emphasis*, 3rd edn Human Kinetics: Champaign, IL, 1999, pp 15–40.

25 Schmidt RA, Lee TD. Central contributions to motor control (Chapter 6). In: *Motor Control and Learning: A behavioral Emphasis*, 3rd edn Human Kinetics: Champaign, IL, 1999, pp 131–168.

26 Polcyn AF, Lipsitz LA, Casey Kerrigan D, Collins JJ. Age-related changes in the initiation of gait: degradation of central mechanisms for momentum generation. *Arch Phys Med Rehabil* 1998; **79:** 1582–1589.

27 Chang H, Krebs DE, McGibbon CA. *Gait initiation strategies in elders*, dissertation. MGH Institude of Health Professions: Boston, MA, 1998.

28 Rogers MW, Kukulka CG, Brunt D, Cain TD, Hanke TA. The influence of stimulus cue on the initiation of stepping in young and older adults. *Arch Phys Med Rehabil* 2001; **82:** 619–624.

29 Rosin R, Topka H, Dichgans J. Gait initiation in Parkinson's disease. *Mov Disord* 1997; **12:** 682–690.

30 Elble RJ, Cousins R, Leffler K, Hughes L. Gait initiation by patients with lower-half parkinsonism. *Brain* 1996; **119:** 1705–1716.

31 Gantchev N, Vialllet F, Aurenty R, Massion J. Impairment of posturo-kinetic co-ordination during initiation of forward oriented stepping movements in parkinsonian patients. *Electroenceph Clin Neurophysiol* 1996; **101:** 110–120.

32 Hesse S, Frank R, Jahnke M, Dawson M, Sarkodie-Gyan T, Mauritz K-H. Asymmetry of gait initiation in hemiparetic stroke subjects. *Arch Phys Med Rehabil* 1997; **78:** 719–724.

33 Kirker SGB, Simpson DS, Jenner JR, Wing AM. Stepping before standing: hip muscle function in stepping and standing balance after stroke. *J Neurol Neurosurg Psychiatry* 2000; **68:** 458–464.

34 Brunt D, Vander Linden DW, Behrman AL. The relation between limb loading and control parameters of gait initiation in persons with stroke. *Arch Phys Med Rehabil* 1995; **76:** 627–634.

35 Miller CA, Verstraete MC. A mechanical energy analysis of gait initiation. *Gait Posture* 1999; **9:** 158–166.

36 Chang H, Krebs DE. Dynamic balance control in elders: gait initiation assessment as a screening tool. *Arch Phys Med Rehabil* 1999; **80:** 490–494.

37 International Standards for Neurological and Functional Classification of Spinal Cord Injury In: Ditunno JF (chairman). American Spinal Injury Association: Chicago, 1996.

38 Hass BM, Bergstrom E, Jamous A, Bennie A. The inter rater reliability of the original and of the modified Ashworth Scale for the assessment of spasticity in patients with spinal cord injury. *Spinal Cord* 1996; **34:** 560–564.

39 Keogh J, Sugden D. *Movement Skill Development*. Macmillan Publishing Corp: New York, 1986, pp 278–282.

40 Beling J, Wolfe GA, Allen KA, Boyle JM. Lower extremity preference during gross and fine motor skills performed in sitting and standing posture. *JOSPT* 1998; **28:** 400–404.

41 Belanger AY, Noel G, Cote C. A comparison of contractile properties in the preferred and nonpreferred leg in a mixed sample of dystrophic patients. *Am J Phys Med Rehabil* 1991; **70:** 201–205.

42 Demura S, Yamaji S, Goshi F, Nagasawa Y. Lateral dominance of legs in maximal muscle power, muscular endurance, and grading ability. *Percept Motor Skills* 2001; **93:** 11–23.

43 Sadeghi H, Allard P, Prince F, Labelle H. Symmetry and limb dominance in able-bodied gait: a review. *Gait Posture* 2000; **12:** 34–45.

44 Malouin F, Richards CL. Preparatory adjustments during gait initiation in 4–6 year-old children. *Gait Posture* 2000; **11:** 239–253.

45 Nissan M, Whittle MW. Initiation of gait in normal subjects: a preliminary study. *Biomed Eng (Berl)* 1990; **12:** 165–171.