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Original Article

Application of Digital Volume Pulse Analysis in Patients with Spinal Cord Injury

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Orthostatic hypotension is a common complication following spinal cord injury (SCI). However, an easy method to quantify the degree of vasomotor impairment below the level of injury is lacking. We postulated that SCI patients with different sympathetic reserves exhibited different digital volume pulse contours. Thirty-one patients with high chronic SCI (above the T6 neurologic level) and 28 low-level SCI patients (below T6) were recruited. Thirty-two age- and BMI-matched healthy participants were enrolled in the control group. All participants were positioned on a tilting table for five minutes in each of the following: supine rest (SR), 60-degree head-up tilt (HUT), and recovery to supine position. Digital volume pulse (DVP), heart rate variability (HRV), and blood pressure were measured. The reflection index (RI) was calculated as the amplitude of reflection wave divided by directly-transmitted wave. The RI ratio is the RI value in the fifth minute during the HUT position divided by RI in SR. Low frequency to high frequency power ratio (LF/HF), high frequency power (HFP), normalized low frequency power (LFn) and high frequency power (HFn) were recorded in HRV analysis. Our results revealed that patients with a higher level of injury had a reduced reflection wave of DVP in SR and HUT. High-level SCI patients also had a smaller RI ratio. Additionally, the increase of LF/HF during the transition from SR to HUT was attenuated in high SCI patients. However, the decrease of HF power was normally preserved in high SCI patients. We concluded that posture change alters the contour of the pulse wave, which is related to the level of injury. The RI ratio could be used to quantify the degree of vasoconstriction impairment below the injury level in SCI patients. (Tw J Phys Med Rehabil 2012; 40(4): 189 - 196)

Key Words: photoplethysmography, orthostatic hypotension, heart rate variability, spinal cord injuries

INTRODUCTION

Orthostatic hypotension is a common complication in spinal cord injury (SCI) patients, especially among those with an injury above the sixth thoracic neurologic level (T6) and those with a complete lesion.[1,2] The severity of orthostatic hypotension is related to the level of injury; the more limited the sympathetic reserve, the more severe the postural hypotension. Although the pathophysiology of orthostatic hypotension is believed to involve a number of factors, including abnormal control

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of arteriolar tone below the level of injury, decreased venous return, and cardiac sympathetic deactivation,[2-4] vasomotor dysfunction due to sympathetic denervation is reported to be the predominant cause.[1,3-6] Unfortunately, no convenient tool is clinically available to quantify the impairment of arteriolar dysfunction.

Analysis of the peripheral pulse waveform to assess arterial properties began in the nineteenth century. The digital volume pulse (DVP) analysis is composed of a direct wave and a reflective wave. The systolic component of the DVP waveform is characterized by a forward-moving pressure wave transmitted along a direct path from the left ventricle to the finger. The diastolic component of the DVP describes the transmission of pressure waves along the aorta to the small arteries in the lower body, where they are then reflected back along the aorta as a reflected wave, travelling to the finger. The size of the reflected wave is determined mainly by the arterial tone of the small muscular arteries distal to the conduit arteries but proximal to the resistance arteries that determine blood pressure. Therefore, pulse wave analysis might indicate the degree of vasomotor impairment below the level of spinal cord injury.

We postulated that SCI patients with different degrees of sympathetic reserve exhibited different digital volume pulse contours in supine rest or orthostatic stress.

METHODS

Fifty-nine patients with traumatic SCI were classified into high or low-level injury. Participants in the high group (N=31) had an injury above T6 neurologic level while those in the low group (N=28) had an injury below or equal to T6 neurological level. The duration of SCI was at least 3 months. Additionally, 32 age- and BMI-matched healthy participants were recruited and formed the control group. Those with cardiovascular illnesses were excluded. Age, gender, disease duration, body height, body weight and BMI were recorded. All patients were assessed using the International Standards for Neurological Classification of Spinal Cord Injury in 2000, which measured the motor, sensory, and neurologic level, as well as the completeness of injury. Participants were asked to refrain from caffeine, alcohol, or staying up late at night during the 24 hours preceding the test. Food or water intake was prohibited two hours before the test.

Before the test, all the participants were asked to rest in a supine position for 15 minutes in a quiet and temperature-controlled testing room. The testing protocol consisted of three components: supine rest (SR), head-up tilt at 60 degrees (HUT), and recovery to supine rest for 5 minutes respectively. Systolic and diastolic blood pressure (SBP and DBP, respectively), heart rate variability (HRV), and DVP were measured simultaneously. DVP and blood pressure values were recorded at minutes 1, 3, and 5 during each posture.

The DVP is assessed using a photoelectric plethysmograph (Micro Medical Trace, PT1000) that measures pulsatile changes in blood volume during the cardiac cycle, and records two values: the reflection index and the stiffness index (RI and SI, respectively). The RI equals the amplitude of reflection wave divided by that of the directly-transmitted wave. The SI, on the other hand, equals the body height divided by the peak-to-peak, or pulse propagating time.[7,8] Finally, the RI ratio is the RI value in HUT at the 5th minute divided by RI in supine rest. This method has been validated in a variety of settings and diseases.[7-10]According to the device program, each value represents a ten-second average of data. The recorded SI and RI values were processed to determine a final value. Briefly, the first three SI values produced a median value. If the next two values were within 10% of the median, the three values (median, 4th, and 5th value) were averaged. If one or both of these additional values differed from the median by more than 10%, DVP was continuously recorded until another two new values were obtained. The five values were ranked by size and yielded a new median. The 2nd and 4th values were averaged with the median if they were within 10% of the median value. If not, two new values were obtained, bringing the total to seven values. The process was repeated like this until the two values nearest the median could be averaged. The three RI values selected to be averaged were based on the chosen SI data. Test-retest reliability of the measure was determined in 10 subjects on separate days. The intra-class correlation coefficients of SI and RI were 0.99 and 0.93, respectively.

Spectral analysis of HRV was employed to evaluate the cardiac autonomic nervous system (ANS) activity. Briefly, power spectra were calculated by computing the squared magnitude of the fast Fourier transform based on data points obtained from a 300 second tachometer signal. The recorded ECG signals were retrieved to measure the consecutive R-R intervals, or the time intervals between successive pairs of QRS complexes, by using specialized software. The main outcome variables in the frequency domain included the following: total power (TP), power spectral densities in very low frequency (VLF; 0-0.04 Hz), low frequency (LF; 0.05-0.15 Hz), and high frequency (HF; 0.15-0.40), the normalized LF and HF (i.e., LFn = 100 X LF/[TP-VLF] and HFn = 100 X HF/[TP-VLF], respectively), and the ratio of LF to HF (LF/HF). Vagal cardiac activity is the major contributor to the HF component. Although the LF rhythm appears to have a widespread neural genesis, LFn mainly reflects the sympathetic modulation of the heart. Finally, the LF/HF ratio is considered to mirror sympatho-vagal balance or to reflect sympathetic modulations.[11,12]

Data were expressed as mean ± standard error of the mean (SEM). All statistical analyses were performed using the SPSS version 18.0 software package. A cross-table Chi-square test was used to compare the demographic data of all the participants. A one-way analysis of variance (ANOVA) followed by Bonferroni post hoc test was used to compare differences between the three groups (high SCI, low SCI, and control) on blood pressure, RI, and HRV. Statistical significance was defined as P value of < 0.05.

RESULTS

AS denoted in Table 1, the three groups did not differ in age, gender, disease duration, body height, body weight, or BMI. Although the proportion of patients with a complete lesion was higher in the low-level SCI group, this difference should not interfere with the interpretation of data.

During the HUT condition, SBP, DBP, and RI values among high-level SCI patients gradually dropped and reached stable values at three to five minutes. As illustrated in Figure 1A and 1B, SBP and DBP significantly decreased in patients with high-level SCI during postural change. Although high-level SCI patients demonstrated a lower heart rate during supine rest, the cardioacceleration response during postural change was similar among the three groups (Figure 1C).

Digital volume pulse wave analysis revealed that the reflection wave diminished progressively from SR to HUT conditions as indicated by a decreased RI (Figure 2A). The RI during the HUT condition as well as the RI ratio were significantly different between each of the groups. Specifically, the RI ratio was lowest in high level SCI group and highest in the control group (Figure 2B).

The HRV results were displayed in Figure 3A and 3B. Unlike the control group, the high SCI group did not exhibit an increase in LF/HF from SR to HUT, but experienced a normal decrease in HF power. Normalized LF and HF also showed diminished change in sympathetic and parasympathetic balance in the high SCI group during postural change (Figure 3C and D).

Table 1. Demographic data

	High	Low	Control	P-value
Number	31	28	32	
Age(year)	39.2 ± 2.6	37.1 ± 2.4	39.4 ± 3.4	0.834
Duration(month)	52.5 ± 11.6	81.9 ± 18.4		0.173
BMI	22.8 ± 0.8	22.6 ± 0.8	23.6 ± 0.6	0.632
Height(cm)	168.7 ± 1.4	167.4 ± 1.0	169.2 ± 1.5	0.642
Weight	65.9 ± 2.3	63.6 ± 2.5	67.5 ± 1.8	0.469
Gender (M:F)	25:6	18:10	29:3	0.158
Complete: incomplete	7:24	19:9		0.001*

*significant difference (P<0.05)

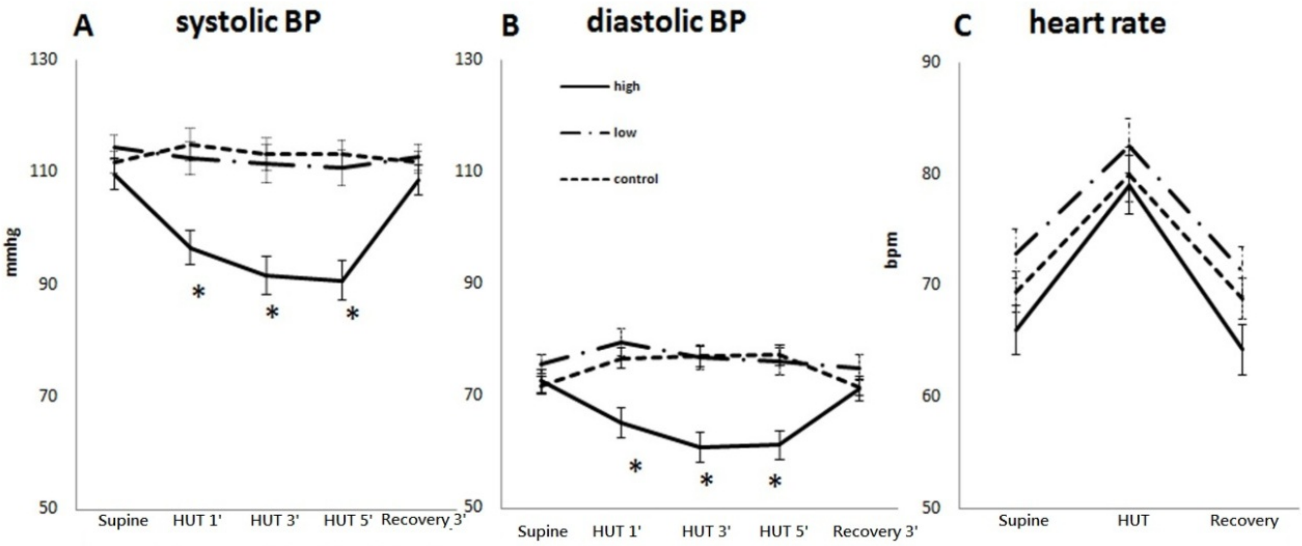

Figure 1A and 1B. The systolic and diastolic blood pressure recorded at SR, the 1st, 3rd, and 5th minute of HUT, and recovery phase are demonstrated.
*one way ANOVA followed by Bonferonni’s post hoc test. Significant difference exists between high level SCI vs. control and low level SCI, P<0.05.
Figure 1C. The heart rate recorded at SR, HUT, and recovery phase among the three groups are shown.

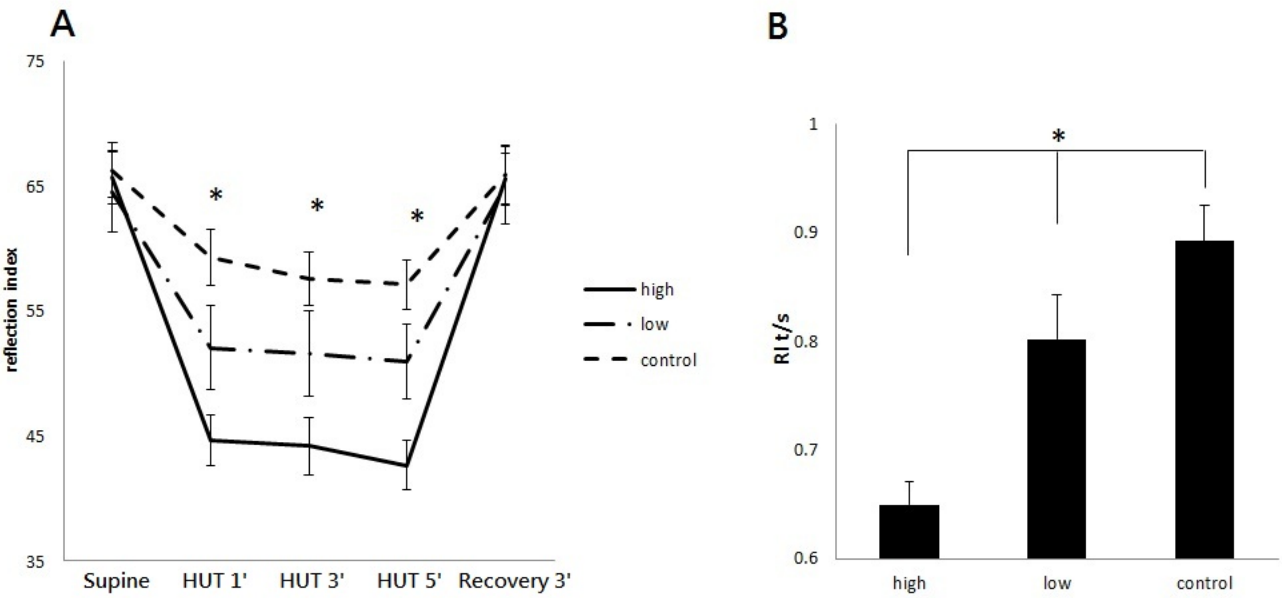

Figure 2A. The reflection index recorded at SR, the 1st, 3rd, and 5th minute of HUT, and recovery phase are shown.
Figure 2B. The ratio of reflection index during HUT to reflection index during SR is demonstrated.
*one way ANOVA followed by Bonferonni’s post hoc test. Significant difference exists between every two groups, P< 0.05.

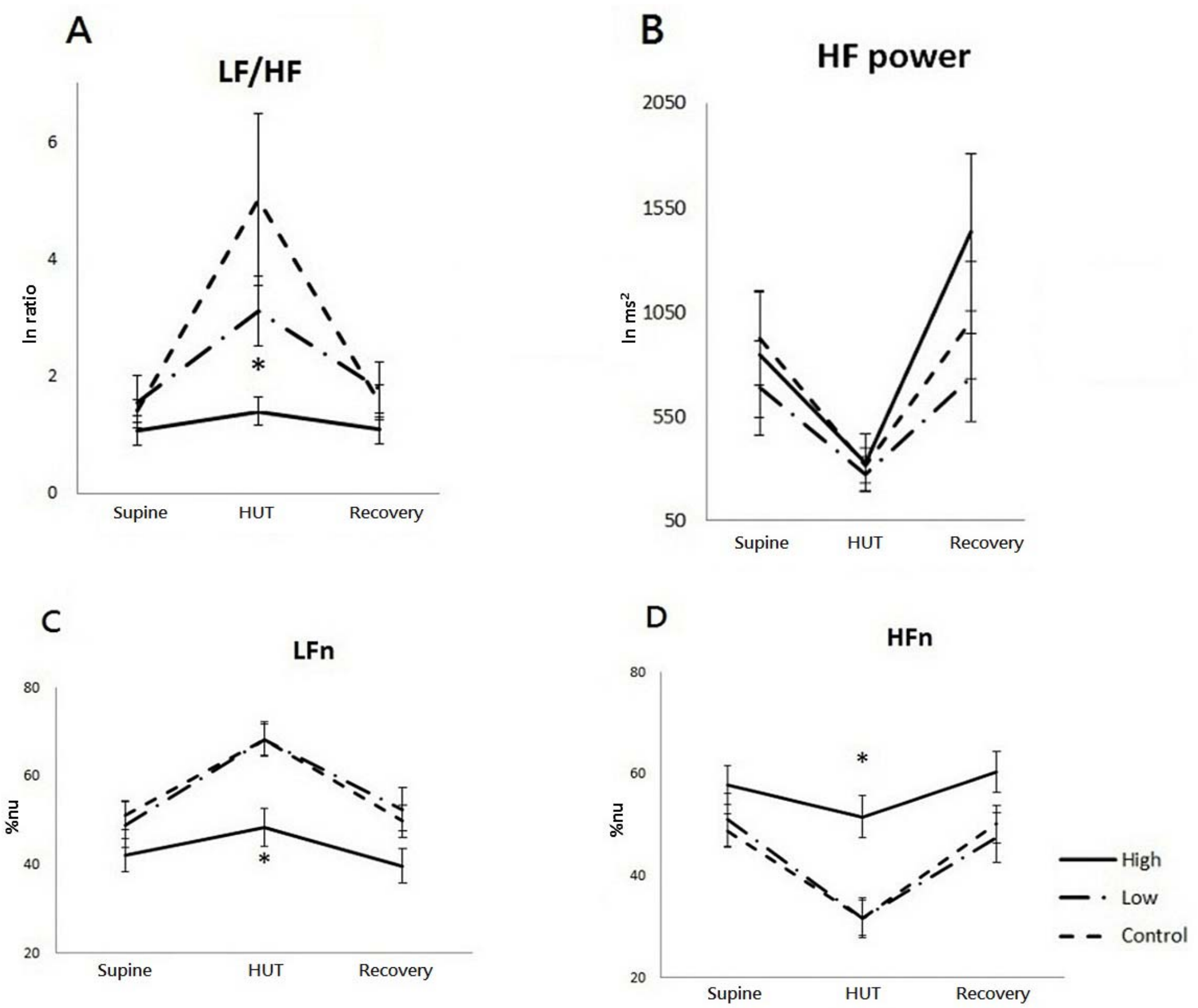

Figure 3. The ratio of low frequency power to high frequency power (LF/HF), high frequency (HF) power, normalized low frequency power (LFn), and normalized high frequency power (HFn) at SR, HUT, and recovery phase among the three groups are demonstrated.
*one way ANOVA followed by Bonferonni's post hoc test. Significant difference exists between high level SCI vs. control and low level SCI, $P<0.05$.

DISCUSSION

To the best of our knowledge, this is the first study to prove that the pulse wave contour changes during postural change and that its reflection index ratio varies based on the SCI level. High-level SCI patients showed much lower RI ratios compared with low-level SCI patients. The pathomechanism of a pronounced decrease in the RI ratio in SCI patients, reflecting reduced diastolic wave reflection from the lower body, may result from impaired vasoconstriction or peripheral pooling during HUT.[8-10,13]

In the present study, the high-level SCI patients exhibited progressively decreased SBP/DBP/RI and reduced LF/HF increase while transitioning from SR to HUT positions, suggesting a decreased reflection wave and sympathetic deactivation. Compared to the control group, the low-level SCI patients also exhibited a decreased RI ratio, but retained an intact HRV response during postural change. These experimental findings suggest arteriole dysfunction and cardiac sympathetic deactivation result in orthostatic hypotension among high-level SCI patients. On the other hand, intact cardiac autonomic response partially compensates for the impaired arteriole dysfunction in low SCI to maintain blood pressure in orthostatic stress.

The American Spinal Injury Association scale provides a method for determining motor level, sensory level, and sacral sparing. These tests mainly evaluate the function of the lateral corticospinal tract, ventral spinothalamic tract/dorsal column, and distal sacral cord. The RI ratio could be used in a clinical setting to directly evaluate arteriolar vasomotor function in the lower part of the body. Lower body arteriolar vasomotor function is innervated by sympathetic nerves derived from lateral horn of the T5/T6 to L2/L3 segment of the spinal cord, which is neuroanatomically deeper than the lateral corticospinal tract and the ventral spinothalamic tract.[4,5,14,15]

Other tools are also available for evaluating vascular resistance. Previous studies using Doppler ultrasound showed lower blood flow and higher vascular resistance in paralyzed legs of chronic SCI patients.[16,17] Studies evaluating the blood flow in SCI patients by utilizing plethysmography have revealed conflicting results.[18,19] For instance, Hopman et al calculated calf and forearm arterial blood flow in SCI patients with over two years with the condition, and revealed lower leg arterial inflow and higher leg vascular resistance.[19] On the contrary, another study yielded the opposite result. However, the disease duration of subjects in this latter trial was not mentioned.[18] While both Doppler ultrasound and venous occlusion plethysmography measure regional vascular resistance, DVP gauges the systemic vascular resistance, which is more appropriate for evaluating the entire vasomotor impairment in SCI patients. Additionally, while previous studies measured regional vascular resistance in supine position only,[16-19] orthostatic stress was applied in our study to also observe the response of systemic vasomotor tone.

A major limitation of the current study was the lack of direct tools to evaluate sympathetic dysfunction in the arteriole as well as the degree of peripheral pooling.

CONCLUSION

Though less widely used, DVP deserves further consideration because of its simplicity and ease of use. Since we found that the level of injury to dictate the decrease in reflection wave in SCI patients, this measure can be used to quantify the degree of vasomotor dysfunction in SCI population.

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手指容積脈波測量在脊髓損傷患者的應用

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姿態性低血壓在脊髓損傷病人中，是相當常見的後遺症。然而，目前臨床上並沒有一個簡單的評估工具能夠用來量化受傷部位以下的小動脈功能損傷程度。我們假設保有不同程度交感神經功能的脊髓損傷病人，在休息平躺或頭部身體傾斜時，會表現出不同的手指容積脈波波型。本研究收集了三十一名高位慢性脊髓損傷(神經受傷節段高於胸髓第六節)及二十八名低位脊髓損傷病人(神經受傷節段低於等於胸髓第六節)。另收集了三十二名年齡及身體質量指數相似的健康受試者為對照組。所有受試者都在傾斜床上進行平躺休息、頭部身體傾斜抬高六十度、及回復平躺休息三種姿勢各五分鐘。同時測量手指容積脈波、心跳變異率及血壓。反射係數為反射波振福除以直接傳導波振福。反射係數比值為身體傾斜五分鐘時之反射係數除以平躺休息時的反射係數。心跳變異數方面，我們紀錄了低頻功率對高頻功率比值、高頻功率、標準化低頻功率以及標準化高頻功率。結果顯示，高位脊髓損傷病人有明顯的姿勢性低血壓，且手指容積脈波之反射波振福從平躺變換到頭部身體抬高傾斜六十度時有明顯下降的情形，而此下降比率和神經受傷節段顯著有關，高位最多、其次低位、再其次為健康控制組。此外，相較於低位慢性脊髓損傷病人和健康控制組，高位病人從平躺變換到頭部身體抬高傾斜六十度時，其低頻對高頻功率比值增加的幅度較少，但其高頻功率減少的幅度並無不同。綜合以上，姿勢變換重力影響下，手指容積脈波的反射波減少，而且神經受傷節段越高位，則減少越多。反射係數比值可以用來在臨床上，量化脊髓損傷病人的交感神經對小動脈控制異常的程度。（台灣復健醫誌 2012；40(4)：189 - 196）

關鍵詞：脈波(photoplethysmography)，姿態型低血壓(orthostatic hypotension)，心跳變異數(heart rate variability)，脊髓損傷(spinal cord injuries)

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