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Electrical stimulation and virtual reality-guided balance training for managing paraplegia and trunk dysfunction due to spinal cord infarction

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SUMMARY
A 41-year-old woman presented with spinal cord infarction and paraplegia after acute thoracoabdominal aortic dissection. Clinical evaluation revealed the American Spinal Injury Association (ASIA) lower limb exercise score of 0 points and the Functional Assessment for Control of Trunk (FACT) score of 0 points. Conventional physical therapy for 60 days did not significantly improve the paraplegia or FACT score; therefore, belt electrode skeletal muscle electrical stimulation (B-SES) and virtual reality (VR)-guided sitting balance training were introduced for 30 days. She developed independence for all basic movements and her gait was restored using short leg braces and Lofstrand crutches. At discharge, her ASIA lower limb exercise score was 24 and FACT score was 7, with a functional impedance measure motor item of 57, and she could continuously walk for a distance of 150 m. The combination of B-SES and VR-guided balance training may be a feasible therapeutic option after spinal cord infarction.

BACKGROUND
Spinal cord infarction is an acute type of myelopathy caused by spinal artery ischaemia.[1 2] Its incidence is estimated in the range of 5000–8000 cases per year in the USA, given that spinal cord infarction accounts for approximately 1% of all stroke cases.[3 4] Symptoms include paraplegia, sensory loss and bladder and rectal dysfunction that vary depending on the infarction site.[5] Several studies with follow-up periods of ≥3 years reported some improvement in the paraplegia symptoms and associated walking disability.[6 7] Meanwhile, severe paralysis at onset has been associated with poor physical function prognosis.[7] However, owing to the low frequency of occurrence, reports on the rehabilitation of patients with spinal cord infarction are scarce. Therefore, additional evidence is required on the outcomes of patients with severe paraplegia and poor physical prognosis.

A recent systematic review of virtual reality (VR)-guided training suggested its usefulness in improving balance and functional mobility in patients with spinal cord injury.[8] A longitudinal case study revealed that neuromuscular electrical stimulation increased dynamic postural stability in a patient with spinal cord injury.[9] Improved trunk function and balance are essential for regaining walking ability after stroke.[10] Studies with patients recovering from spinal cord infarction using a combination of electrical stimulation and VR-guided training may improve future outcomes in this patient group.[10]

This case report presents a patient with spinal cord infarction that failed to achieve desired improvement with conventional physical therapy but did improve using supplementary lower limb transcutaneous electrical stimulation and VR-guided balance training for paraplegia and trunk function, respectively.

CASE PRESENTATION
A 41-year-old woman was diagnosed with an acute thoracoabdominal aortic dissection (Stanford Type B, DeBakey III b) based on contrast-enhanced CT findings (figure 1A). The patient presented without any signs of vital organ blood supply loss caused by branch arterial obstruction secondary to the dissection and, thus, received conservative treatment. The following day, the patient presented with the paralysis of both lower limbs and the trunk, sensory impairment below the ninth thoracic vertebra, increased tendon reflexes in bilateral lower extremities and bowel and bladder dysfunction. She was diagnosed with spinal cord infarction due to insufficient blood flow in the spinal arteries. Spinal cord MRI was not performed, at the attending surgeon's discretion, and the diagnosis was made according to the criteria proposed by Zalewski *et al*.[11] The criteria for probable periprocedural spinal cord infarction include acute non-traumatic myelopathy and severe acute antigravity muscle deficits, occurring within 12 hours after the onset of thoracoabdominal aortic dissection, in the absence of any plausible alternative diagnoses.[11] Bilateral neurological deficits, increased tendon reflex and bowel and bladder dysfunction further supported the diagnosis of spinal cord infarction. The patient underwent emergent endovascular aortic stent grafting to prevent aortic dissection progression (figure 1B). After about 2 months of acute treatment, the patient was transferred to our hospital for rehabilitation.

INVESTIGATIONS
At the time of her transfer, no limited range of motion or spasticity was observed in the limbs or trunk; however, the American Spinal Injury Association (ASIA) lower extremity motor score was 0, indicating severe flaccid paralysis (table 1). Functional indices are presented in tables 1 and 2. Light touch and pin prick responses were severely

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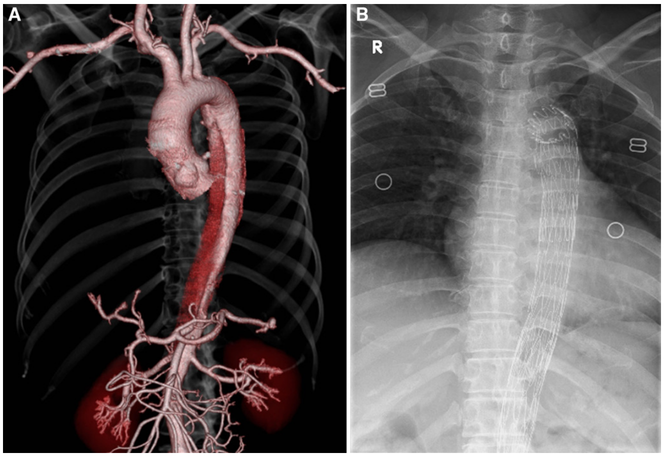

Figure 1 Three-dimensional reconstructed CT angiography of thoracoabdominal aorta at the onset (A). Chest X-ray findings after endovascular aortic stent-grafting (B). (A) The aortic dissection extended from the left subclavian artery to both renal arteries at the onset. (B) Endovascular aortic stent-grafting was performed in the descending aorta distal to the aortic arch.

impaired below the ninth thoracic vertebra level and absent below the second lumbar vertebra level, without signs of sacral sparing (table 2). Additionally, the trunk function was 0 points on the functional assessment for control of trunk (FACT), while the manual muscle test score of the rectus abdominis was 2. The patient required assistance for all movements, such as getting up and maintaining a sitting position without support, and an indwelling urinary catheter was used for bladder management. From the beginning, the patient strongly desired to walk home without using a wheelchair at discharge.

TREATMENT

Details of the conventional physical therapy protocol used in this case are presented in table 3. Changes to the ASIA lower limb total motor score and FACT scores over time are presented in figure 2. To regain independence in basic movements, training for transferring and sitting up movements was provided. In addition, since the patient had a desire to reacquire the ability to walk, walking training was conducted using bilateral knee–ankle–foot orthoses and a load relief type rehabilitation lift SP-1000 (Moritoh, Aichi, Japan). The rehabilitation lift used in this case enabled weight unloading by lifting the body with the arm placed on top of the lift. Meanwhile, the presence of wheels supported walking practice by maintaining weight unloading. The patient was instructed to push the lift forward using their arms, and the physical therapist assisted from behind, helping the patient swing forward the leg that was fixed with the long leg orthosis. Walking training was performed at approximately 100 m/day, depending on the patient's vital signs and fatigue level. The conventional physical therapy described in table 3 was provided 180 min on weekdays, as supported by medical insurance coverage. Several physical therapists provided patient care. After the patient completed the aforementioned physical therapy programme for approximately 60 days, grooming and dressing both improved to 7 points on the functional independence measure (FIM). Although no obvious change was noted in trunk function FACT score, the patient was able to maintain a seated position in clinical situations without the use of a brace, and only light assistance was required for transfer tasks to prevent slips and falls. However, the transfer operation in the ward was 1 point on the FIM, as it sometimes required two caregivers depending on the skill of the caregiver. Additionally, only a few changes were observed in the lower limb function, and muscle contraction was not observed in either of the lower limbs.

Based on these results, in addition to conventional physical therapy, B-SES therapy using a general therapy electrical stimulator (Homerion Laboratory Tokyo, Japan) was initiated on hospital day 60. The entire belt of the B-SES device acts as an electrode that can induce contraction in the quadriceps, hamstrings, triceps surae and tibialis anterior muscles when wrapped around the waist, thigh and distal lower limbs (figure 3). B-SES was performed as self-training separately from physical therapy for 20 min a day, five times a week, at a frequency of 20 Hz, with the maximum intensity at which the muscle contraction appeared and the pain could be tolerated. Several weeks after the initiation of B-SES, slight muscle contraction of the lower limbs was observed (table 1). From the state where only reflective movements of the lower limbs were observed, intentional autonomous movements became gradually feasible, and the ASIA lower limb mobility score improved to 17 points, 30 days after the initiation of B-SES (figure 2). The patient began walking with light assistance using a walker without fixing the knee joints using a knee–ankle–foot orthosis. Although the patient showed resistance to self-catheterisation for urination at the beginning of her hospitalisation, the indwelling

Table 1 Progress in total score (points) of various functional indices

	At admission	cPT	cPT	After B-SES	After VR	cPT	At discharge
Days after admission (hospital day)	0	30	60	90	120	150	180
ASIA impairment scale	A	A	A	C	C	C	C
ASIA Motor Score (upper limbs)	50	50	50	50	50	50	50
ASIA Motor Score (lower limbs)	0	0	2	17	20	24	24
ASIA Sensory Score (light touch)	72	72	74	78	76	77	70
ASIA Sensory Score (pin prick)	72	72	74	72	77	77	78
ASIA neurological level of injury	T9	T9	T9	T8	T8	T8	T8
FACT	0	1	2	2	5	5	7
FIM motor item	23	40	40	41	45	53	57
Total walking distance per day (mean)	0 m	40 m	100 m	120 m	120 m	600 m	600 m
Walkable distance	0 m	10 m	20 m	60 m	100 m	150 m	150 m

ASIA, American Spinal Injury Association; B-SES, belt electrode skeletal muscle electrical stimulation; cPT, conventional physical therapy; FACT, functional assessment for control of trunk; FIM, functional independence measure; T8, eighth thoracic vertebra; T9, ninth thoracic vertebra; VR, virtual reality.

Table 2 Changes to ASIA and FACT score items

	At admission	cPT	cPT	After B-SES	After VR	cPT	At discharge
Days after admission (hospital day)	0	30	60	90	120	150	180
ASIA Motor Score (upper limbs)							
Elbow flexors, right/left	5/5	5/5	5/5	5/5	5/5	5/5	5/5
Wrist extensors, right/left	5/5	5/5	5/5	5/5	5/5	5/5	5/5
Elbow extensors, right/left	5/5	5/5	5/5	5/5	5/5	5/5	5/5
Finger flexors, right/left	5/5	5/5	5/5	5/5	5/5	5/5	5/5
Finger abductors, right/left	5/5	5/5	5/5	5/5	5/5	5/5	5/5
ASIA Motor Score (lower limbs)							
Hip flexors, right/left	0/0	0/0	0/0	1/2	2/2	2/2	2/2
Knee extensors, right/left	0/0	0/0	1/1	2/2	2/2	4/4	4/4
Ankle dorsiflexors, right/left	0/0	0/0	0/0	1/2	2/2	2/2	2/2
Long toe extensors, right/left	0/0	0/0	0/0	1/2	2/2	2/2	2/2
Ankle plantar flexors, right/left	0/0	0/0	0/0	2/2	2/2	2/2	2/2
ASIA Sensory Score (light touch)							
C2-T8, right/left	2/2	2/2	2/2	2/2	2/2	2/2	2/2
T9, right/left	2/2	2/2	2/2	1/1	1/1	1/1	1/1
T10, right/left	1/1	1/1	1/1	1/1	1/1	1/1	1/1
T11, right/left	1/1	1/1	1/1	1/1	1/1	1/1	1/1
T12, right/left	1/1	1/1	1/1	1/1	1/1	1/1	1/1
L1, right/left	1/1	1/1	1/1	1/1	1/1	1/1	1/1
L2, right/left	0/0	0/0	1/1	1/1	1/1	1/1	0/0
L3, right/left	0/0	0/0	0/0	1/1	1/1	1/1	0/0
L4, right/left	0/0	0/0	0/0	1/1	1/1	1/1	0/0
L5, right/left	0/0	0/0	0/0	1/1	0/0	1/0	0/0
S1, right/left	0/0	0/0	0/0	0/0	0/0	0/0	0/0
S2-S5, right/left	0/0	0/0	0/0	0/0	0/0	0/0	0/0
ASIA Sensory Score (pin prick)							
C2-T8, right/left	2/2	2/2	2/2	2/2	2/2	2/2	2/2
T9, right/left	2/2	2/2	2/2	1/1	1/1	1/1	1/1
T10, right/left	1/1	1/1	1/1	1/1	1/1	1/1	1/1
T11, right/left	1/1	1/1	1/1	1/1	1/1	1/1	1/1
T12, right/left	1/1	1/1	1/1	1/1	1/1	1/1	1/1
L1, right/left	1/0	1/1	1/1	1/1	1/1	1/1	1/1
L2, right/left	1/0	0/0	1/1	1/1	1/1	1/1	1/1
L3, right/left	0/0	0/0	0/0	0/0	1/1	1/1	1/1
L4, right/left	0/0	0/0	0/0	0/0	1/1	1/1	1/1
L5, right/left	0/0	0/0	0/0	0/0	1/0	1/0	1/0
S1, right/left	0/0	0/0	0/0	0/0	0/0	0/0	1/0
S2-S5, right/left	0/0	0/0	0/0	0/0	0/0	0/0	0/0
FACT							
1. Ability to sit upright for more than 10 s when grabbing a railing or seat surface using the upper limbs. **Yes/no: 1/0 points**	0	1	1	1	1	1	1
2. Ability to sit upright for more than 10 s without using the upper limbs. **Yes/no: 1/0 points**	0	0	1	1	1	1	1
3. Ability to grab using either the left or right hand the ankle on the other side and then return to the original position. **Yes/no: 1/0 points**	0	0	0	0	0	0	0
4. Ability to move at least 10 cm to both the right and left side while lifting the bilateral buttocks. **Yes/no: 2/0 points**	0	0	0	0	0	0	0
5. Ability to lift the unilateral buttock from the seat for at least 3 s (bilateral). **Bilateral/unilateral/unable: 2/1/0 points**	0	0	0	0	0	0	2
6. Ability to lift right or left thigh and remain for at least 3 s with the sole of the foot not touching the ground (bilateral). **Bilateral/unilateral/unable: 2/1/0 points**	0	0	0	0	0	0	0

Continued

Table 2 Continued

	At admission	cPT	cPT	After B-SES	After VR	cPT	At discharge
7. Ability to lift both the right and left thighs with both feet not touching the ground for at least 3 s. **Yes/no: 2/0 points**	0	0	0	0	0	0	0
8. Ability to lift buttocks one side at a time and move both forward and backward with the bottom. **Yes/no: 3/0 points**	0	0	0	0	0	0	0
9. The examiner should touch the seat surface 20 cm posterior to the sacral bone. The examinee should look over their shoulder and say how many fingers the examiner is showing, which should be changed three times at 1 s intervals. **Able/unable: 3/0 points**	0	0	0	0	0	0	0
10. Ability to raise the right or left upper limb (shoulder joint bending) with maximum effort; ability to the ground at the middle position of the adduction/extorsion of the shoulder joint. **Yes/no: 3/0 points**	0	0	0	0	3	3	3

ASIA, American Spinal Injury Association; B-SES, belt electrode skeletal muscle electrical stimulation; C, cervical vertebra; cPT, conventional physical therapy; FACT, functional assessment of control of trunk; FIM, functional impedance measure; L, lumbar vertebra; S, sacral spine; T, thoracic vertebra; VR, virtual reality.

catheterisation was switched to intermittent self-catheterisation on hospital day 70 under nurse guidance. In contrast, during this period, although we approached trunk function through basic movements and balance training in the sitting position, no changes were observed in the FACT score, trunk function index or instability in the sitting position, indicating that independence in transfer movements was not achieved.

To improve trunk function, we tried sitting-position balance training by VR using mediVR KAGURA (mediVR, Toyonaka, Japan) (figure 4). This device is used to encourage a reaching movement with the patient in a sitting position by having them attempting to touch a falling object that appears in a three-dimensional virtual space with a hand-held controller.[12–14] It promotes repeating various reaching movements by adjusting the distance and angle to the falling object and speed of falling. We introduced it several times as part of the physiotherapy, using customised distance and speed for the acquisition of the falling objects to account for approximately 70% of the total movements. Later, since the patient could perform the VR training safely by herself, she performed it for 20 min a day, five times a week, as a self-training replacement for B-SES. When VR training was introduced, the number of reaches per session of self-training was about 300; this figure became 600 by the end of the training programme. Therefore, the FACT score improved from 2 points before the initiation of VR training to 5 points (figure 2); the previous problematic trunk instability during transfer movements resolved, and the transfer movements in the ward were corrected independently. For walking, the knee–ankle–foot orthoses were changed to ankle–foot orthoses, and the patient started walking under supervision using a walker.

Following this, for approximately 60 days until discharge, movement training was conducted under the expected in-home setting after discharge, while changing the self-training from VR to walking training, the distance increased from 120 m to 600 m. The patient used an ankle–foot orthosis for both lower limbs and a Lofstrand crutch at the time of discharge and was moving a short distance in the house. She was able to put on the orthoses. The light touch examination revealed reduced response at discharge, likely due to myalgia in the lower extremities (tables 1 and 2). Although no improvement was seen in urinary function, the patient could manage bladder emptying using intermittent self-catheterisation. As defecation required a nurse's intervention, home-visit nursing care was planned.

OUTCOME AND FOLLOW-UP

After discharge, the patient continued to undergo physical therapy through home-visit rehabilitation for 6 months, henceforth with no significant change in physical function. The patient

Table 3 Conventional physical therapy protocol

Days after admission (hospital day)	0–30	30–60	60–90	90–120	120–150	150–180
Transferring operation practice	*	*	*	*		
Sitting-up practice	*	*	*			
Roll-over practice	*	*	*			
Range-of-motion exercise	*	*	*	*		
Upright position training on the stand	*	*	*			
Upper limb muscle-strengthening exercises	*	*	*			
Wheelchair driving practice	*					
Walking practice	*	*	*	*	*	*
Upright practice				*	*	*
Lower limb muscle-strengthening exercises				*	*	*
Applied walking with obstacles						*
Outdoor walking practice						*

*Indicates that activity was performed.

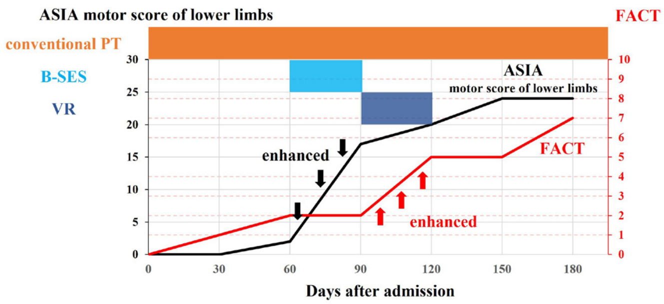

Figure 2 Rehabilitation schedule and changes in ASIA total motor score of the lower limbs and FACT scores. ASIA, American Spinal Injury Association motor score; B-SES, belt electrode skeletal muscle electrical stimulation; FACT, Functional Assessment for Control of Trunk; PT, physical therapy; VR, virtual reality.

is using a Lofstrand crutch while walking and a wheelchair while sitting.

DISCUSSION

Higher ASIA impairment scale scores at onset are reportedly associated with poor long-term prognosis of physical function in patients with spinal cord infarction.[6 7] In the current case, where the prognosis was poor, we hypothesise that B-SES and VR-guided body trunk training may have contributed to the improvement of the ASIA scores of the lower limb movement and trunk function index, respectively (table 1 and figure 2). Both modalities were feasible, and no adverse events or safety concerns were observed. The present findings are based on a single case and should be interpreted with caution; nevertheless, they suggest that B-SES and VR-guided training may be used in clinical practice, where the relevant equipment is available.

Electrical stimuli reportedly do not contribute towards improving the walking ability in a patient with spinal cord injury; rather they only prevent skeletal muscle atrophy, impact postural stability or positively affect lower extremity skeletal muscle metabolic activity shown by positron emission tomography.[9 15–18] A recent systematic review of five controlled trials evaluating the impact of neuromuscular electrical stimulation therapy showed no strong evidence supporting its superiority over other treatment strategies used to gain strength in partially paralysed muscles after spinal cord injury.[16] However, in the present case, electrical stimulation seemed to improve lower limb function, further improving walking ability, as the walkable distance tripled from 20 m to 60 m. This discrepancy in findings might be, at least in part, owing to the partially reversible neurological damage present, caused by ischaemia of the spinal artery rather than complete spinal injury.[6 7] Several reports have stated that physical function of patients with spinal cord infarction improves over time.[7 15] In the present case, we speculated that repetitive stimuli input may have activated the spinal nerves that escaped damage (hibernating neurons) and reorganised the remaining neural circuit.

A study of the effect of sitting-position balance training using VR in patients with paraplegia demonstrated that the improvement in balance function index was proportional to the duration of intervention compared with task training, such as the activity of daily living training.[19] This report is consistent with our results, and VR has elements that promote motor learning for balance acquisition.[19–21] The existence of sensory feedback is critical in the motor learning process, and the mediVR KAGURA used in this study can give three types of sensory feedback, including visual, auditory and tactile.[12–14] Such feedback enabled capturing of the reach distance errors from multiple angles, which promoted relearning of sitting balance.[13 14 19–21] Furthermore, using immersive VR with a game-like feature assisted with internal motivation to conduct many reach movements by the patient, which may have been effective for learning.[20 21]

This report only described a single case, and distinguishing its outcomes from the natural disease course is challenging due to the timing of the intervention.[6] That is, it is difficult to confidently say that B-SES and VR mainly contributed to the patient's gains.[6] In addition, the 20 min/day of additional self-training performed in this case might have boosted the improvements

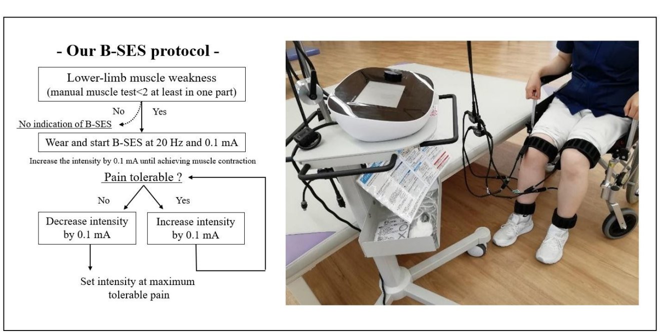

Figure 3 Image of self-training using belt electrode skeletal muscle electrical stimulation. Muscle electrical stimulation was performed in a wheelchair sitting position. For electrostimulation, the belt electrode was attached bilaterally to the proximal thighs (below the pants), distal thighs and ankles. At a frequency of 20 Hz, the intervals of the on and off stimuli were set to 5 and 2 s, respectively. The intensity of the stimulus was gradually increased from 0.1 mA or decreased by 0.1 mA on the display. The intensity was set at the level at which the muscle contraction appeared and set at the maximum tolerable pain. The output strength was often set to about 0.7–1.3 mA in this case. B-SES, belt electrode skeletal muscle electrical stimulation.

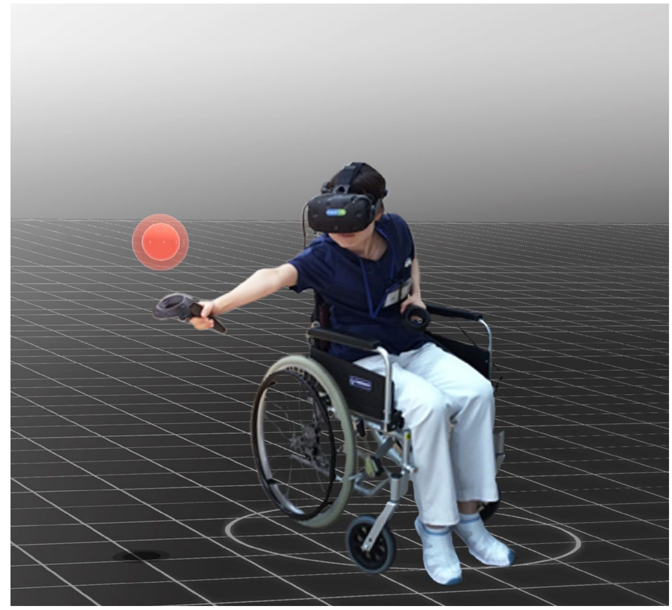

Figure 4 Image of self-training of sitting balance using mediVR KAGURA. The patient wears a head-mounted display and is encouraged to reach to catch a falling object appearing in the three-dimensional virtual space. The difficulty levels can be set by adjusting the size of the falling object and falling speed.

of our patient's symptoms because her functional improvement coincides with the length of time the patient was seen for treatment. In addition, the FACT score is a tool for the assessment of patients with stroke rather than for the assessment of those with spinal cord injury or infarction. Consequently, it is plausible that some improvements in trunk function were not detected by this scale.[22] However, we reported this case of spinal cord infarction since it suggested the possibility that electrical stimulation therapy and sitting-position balance training using VR improved the paraplegic function and the trunk function index, respectively. The benefits of neuromuscular electrical stimulation or VR-guided training have been previously reported,[23–28] and further studies on the clinical effects in patients with spinal cord infarction are expected in the future.

Learning points

- Owing to its low frequency of occurrence, reports on the rehabilitation of patients with spinal cord infarction are scarce.
- The combination of conventional physical therapy with belt electrode skeletal muscle electrical stimulation and virtual reality-guided balance training may have contributed to improving the lower-limb movement and trunk function index, respectively.
- Improved limb and trunk function of patients with spinal cord infarction improved activities of daily living such as walking and transferring.

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Competing interests Yuichiro Murakawa is an employee of mediVR, Inc., a company that holds several patents on VR-guided rehabilitation. Ai Michibata, Miyoko Haraguchi and Hideo Ishikawa have no conflicts of interest to declare.

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