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# EFFICACY OF A THORACOLUMBAR ACTIVE RESISTANCE REHABILITATION TRAINER VERSUS TRADITIONAL BRIDGE EXERCISES IN SPINAL CORD INJURY: A RANDOMIZED CONTROLLED TRIAL

MeiLing Cheng[1,2], FangYong Wang[1,2,3*]
[1]*Rehabilitation Medicine Center, The Second Affiliated Hospital and Yuying Children's Hospital, Wenzhou Medical University, Wenzhou 325000, Zhejiang, China.*
[2]*Department of Spine Surgery, Beijing Bo'ai Hospital, China Rehabilitation Research Center, Beijing 100068, China.*
[3]*School of Rehabilitation, Capital Medical University, Beijing 100068, China.*
[*]*Corresponding Author: FangYong Wang*

**Abstract:** Objective: A thoracolumbar active resistance rehabilitation trainer was developed, aiming to verify its activation effect on the core muscles of the lumbar and abdominal regions in spinal cord injury (SCI) cases and explore the difference in therapeutic efficacy between this trainer and traditional bridge exercises. Methods: A prospective, assessor-blinded randomized controlled trial of 40 SCI inpatients. Participants were allocated to two groups, both alongside conventional rehabilitation. The experimental group received 8 weeks of training with the trainer, while the control group underwent 8 weeks of bridge exercises training. The assessment indicators include surface electromyography, Spinal Cord Independence Measure-III, Walking Index for Spinal Cord Injury, and Japanese Orthopaedic Association scores. Results: The experimental group demonstrated superior abdominal muscle activation versus controls at 8 weeks. Clinically, the experimental group showed greater improvement in functional independence (t=2.599, P=0.019, Cohen'd=1.225), exceeding the minimal clinically important difference (MCID). Both groups achieved MCID in walking ability (WISCI) and lumbar function (JOA), with no significant between-group differences. The trainer was safe and rated higher for convenience and usability. Conclusion: The trainer is safe and more effective than bridge exercises for functional independence in SCI rehabilitation, offering practical advantages for diverse settings.
**Keywords:** Spinal cord injury; Active rehabilitation; Bridge exercise; Spinal cord independence measure

## 1 INTRODUCTION

Spinal cord injury (SCI) causes motor, sensory, and autonomic dysfunction below the injury level, resulting in severe long-term disability[1]. Global incidence ranges from 300,000 to 500,000 new cases annually, with 90,000–120,000 occurring in China[2]. Although moderate-to-high intensity aerobic and resistance training is recommended for improving fitness and muscle strength in SCI[3], research on effective and accessible training methods remains limited.

Current SCI exercise therapies include physical therapy, assistive technology therapy, and advanced therapies[4]. Traditional physical therapy is labor-intensive, prone to therapist fatigue and reduced treatment quality[5]. Robot-assisted training offers precision and personalized adjustment but is expensive and mechanical[6]. Invasive therapies like spinal cord stimulation and brain-computer interfaces have limitations such as infection risks, high cost, and limited motor function improvement[7-8]. Most existing rehabilitation devices rely on specialized centers, lacking portability and applicability in home and community settings[9]. SCI patients often suffer from trunk muscle weakness and reduced core stability, impacting balance and quality of life[10].

To address the limitations of current methods, our team developed a portable thoracolumbar active resistance rehabilitation trainer. This study compared its efficacy with traditional bridge exercises in activating lumbar and abdominal core muscles and improving clinical outcomes in SCI patients. The research aims to offer a practical, accessible training solution for clinical, community, and home-based rehabilitation, support patient recovery, and contribute to advancements in SCI rehabilitation practice.

## 2 MATERIALS AND METHODS

### 2.1 Study Design

This prospective randomized controlled trial was conducted from February to August 2025 in a hospital. The study protocol was approved by the Medical Ethics Committee of China Rehabilitation Research Center (No. 2024-106-01) and adhered to the principles of the Declaration of Helsinki. Written informed consent was obtained from all participants and their guardians prior to study commencement. The trial was registered on the World Health Organization International Clinical Trials Registry Platform – Chinese Clinical Trial Registry (No. ChiCTR2500097098).

### 2.2 Participants

Sample size was determined using G*Power 3.1.9.7 software[11], with an effect size of 0.80, statistical power of 0.80, and α level of 0.05, indicating a requirement of 40 participants[12]. Forty enrolled SCI inpatients were included in the study.

Clinical diagnosis was performed by spinal specialists with over 10 years of experience. Inclusion criteria: (a) individuals aged 18–64 with SCI ; (b)Motor incomplete SCI with the motor level between C7 and L1, and American Spinal Injury Association (ASIA) impairment scale grade C or D; (c) >3 months post-surgery, non-progressive injury; (d) Upper limb muscle strength ≥ grade 4; (e) Ability to maintain level 3 sitting balance; (f) No recent participation in other spinal rehabilitation programs; (g) Signed informed consent. Exclusion criteria: (a) Lower limb radiating pain or pain exacerbation during training; (b) Severe lumbar spinal stenosis, tumor, lumbar disc herniation, spondylolisthesis, etc.; (c) Severe heart disease, hypertension, metabolic diseases, or other conditions unsuitable for exercise training; (d) Severe osteoporosis.

### 2.3 Randomization and Blinding

Randomization was performed at a 1:1 ratio. A computer-generated random sequence ensured balanced group allocation. The random sequence and opaque envelopes containing group assignments were prepared in advance by one researcher. The original randomization list was kept confidential by this researcher and not disclosed. Random envelopes were opened during patient recruitment on the ward with at least two personnel present. Due to the nature of the interventions, blinding of therapists and SCI participants was not feasible. However, outcome assessors and data analysts were blinded to group allocation to ensure impartiality during subjects assessment and data analysis.

### 2.4 Device Design

Our team designed a portable thoracolumbar active resistance rehabilitation trainer (Figure 1), comprising fixation and external mechanisms. The fixation mechanism stabilizes the user, while the external mechanism includes adjustable resistance structures (up to 20 kilogram) and grips. Applying forward or lateral force activates posterior back core muscles via spring-based resistance. Surface electromyography monitored muscle activation, enabling resistance adjustment to optimize training.

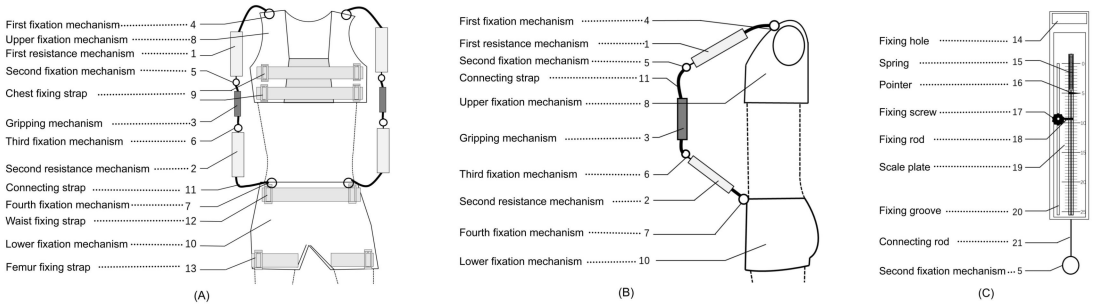


**Figure 1** The Trainer's Design Schematic: (A) Frontal Structure Design Drawing; (B) Lateral structure Design Drawing; (C) Resistance Structure Design Drawing

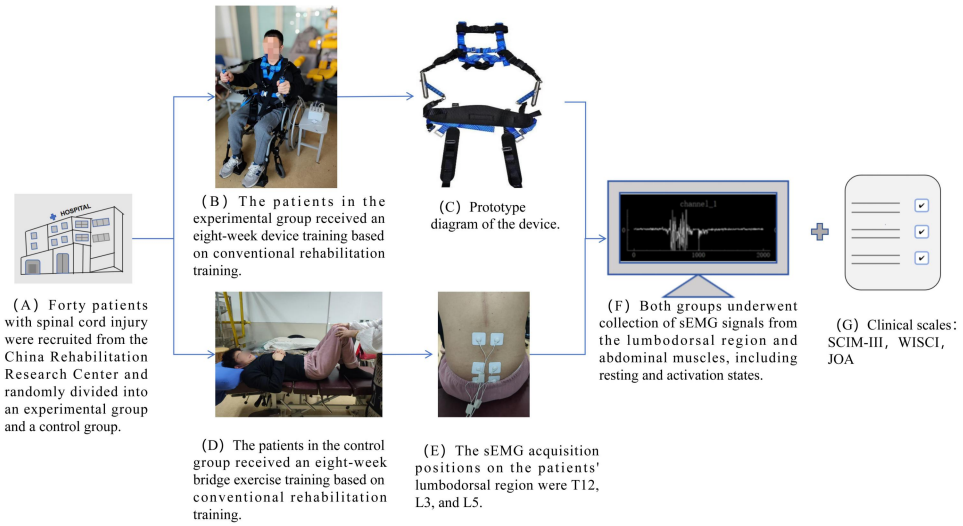


**Figure 2** Schematic Diagram of the Research Process: (A) represents the Recruitment and Grouping of Subjects; (B) Shows a Spinal Cord Injury Subject Performing Core Muscle Training Using a Thoracolumbar Active Rehabilitation

Training Device, with Simultaneous Collection of Surface Electromyography Signals; (C) Shows the Prototype Diagram of the Thoracolumbar Active Resistance Rehabilitation Trainer; (D) Shows a Spinal Cord Injury Subject Performing Traditional Bridge Exercise Training on a Treatment Bed; (E) a Therapist is Collecting Surface Electromyography Signals of the T12, L3, and L5 from the Subject; (F) the Surface Electromyography Signals are Processed and Converted into Recorded Values via Spyder Software (Python 3.11). (G) SCIM-III, WISCI, and JOA Scores were Selected for the Collection of Clinical Indicators

### 2.5 Intervention

Participants were randomly assigned to two groups. The experimental group received 8 weeks of device training. The trainer's donning, adaptation, and training were guided by the same therapist. The control group receiving bridge exercises for 8 weeks. Both groups trained 3 times per week for 30 minutes, in addition to conventional rehabilitation, ensuring exercises avoided fatigue and the valsalva effect. Training intensity was adjusted to cause mild next-day fatigue without affecting daily function. Outcomes including sEMG, Spinal Cord Independence Measure-III (SCIM-III), Walking Index for Spinal Cord Injury (WISCI), and Japanese Orthopaedic Association (JOA) scores were assessed at baseline, 4 weeks, and 8 weeks. The overall research process is shown in Figure 2.

### 2.6 Outcome Measures

#### *2.6.1 Primary outcomes*

In this study, the SCIM-III (assessing daily independence), WISCI (quantifying walking ability), and JOA (evaluating lumbar neurological function) were set as primary outcomes [13-15]. Their minimal clinically important differences (MCIDs) were predefined as 4 points for SCIM-III, 2 points for WISCI (0–20 scale), and 2.5 points for JOA, based on established consensus and literature [16-17].

#### *2.6.2 Secondary outcomes*

sEMG signals were recorded using a 16-channel system at the paravertebral muscles of the twelfth thoracic vertebra (T12), third lumbar vertebra (L3), and fifth lumbar vertebra (L5), and the paraumbilical abdominal muscles, with Resting Value (RV) and Activation Value (AV) analyzed for parameters including Root Mean Square (RMS), Average Electromyography (AEMG), Mean Power Frequency (MPF), and Median Frequency (MF). Safety was evaluated through adverse events, and participant satisfaction surveys were conducted post-intervention to inform future research.

#### *2.7 Statistical analysis*

All analyses were performed using SPSS software (Version 27.0, IBM Corporation, Armonk, New York, USA). Electromyography (EMG) data were collected and processed via a 16-channel system to obtain standardized parameters. Normally distributed data were expressed as mean ± standard deviation, while skewed data were presented as median and interquartile range. Inter-group differences were analyzed using Independent samples t-tests and Mann-Whitney U-tests, and intra-group differences were assessed by repeated-measures analysis of variance. Statistical significance was set at $P < 0.05$. Post-hoc multiple comparisons applied the Bonferroni correction [18].

## 3 RESULTS

### 3.1 Participant Characteristics

98 SCI cases hospitalized at Beijing Bo'ai hospital between February 2025 and August 2025 were screened. 40 cases diagnosed with SCI who met the inclusion criteria participated. Written informed consent was obtained from subjects and guardians in the ward before data collection. Baseline characteristics are detailed in Table 1.

**Table 1** Participant Characteristics (Experimental and Control Groups Each Included 20 SCI Cases)

| Indicator | Experimental Group | Control Group | t/z | P |
|---|---|---|---|---|
| Numbers | 20 | 20 | - | - |
| Gender(M:F) | 12:8 | 14:6 | - | - |
| Age(year) | 41.9±14.004 | 37.556±14.85 | 0.654 | 0.522 |
| Height(cm) | 165.9±6.657 | 173.556±7.667 | 2.11 | 0.051 |
| BMI（kg/m2） | 23.502±3.691 | 23.312±4.939 | 0.095 | 0.925 |
| Duration of Disease(day) | 166.1±49.751 | 163±47.692 | 0.139 | 0.891 |
| Injury Segment (Cervical: Thoracolumbar) | 3:17 | 2:18 | - | - |
| ASIA grade（C:D） | 11:9 | 10:10 | - | - |

Note: The Normal data are expressed as mean and standard deviation. (M:F: Male:female. BMI: body mass index.)

### 3.2 sEMG

#### *3.2.1. Motor unit recruitment capacity*

(1) Experimental Group: RMS and AEMG (RV vs. AV)

As shown in Figure 3, the AV of RMS at the paravertebral muscles of T12, L3, and the abdomen were significantly higher than RV in all three assessments ($P < 0.05$). Similarly, the AV of AEMG at the paravertebral muscles of T12 and L5 were

significantly higher than RV in all three assessments ($P < 0.05$). Meanwhile, the AV of L5 RMS and L3 AEMG were significantly higher than RV in both post-intervention assessments ($P < 0.05$). In addition, the AV of abdominal AEMG was significantly higher than RV in the comparisons at baseline and two months after the intervention ($P < 0.05$).

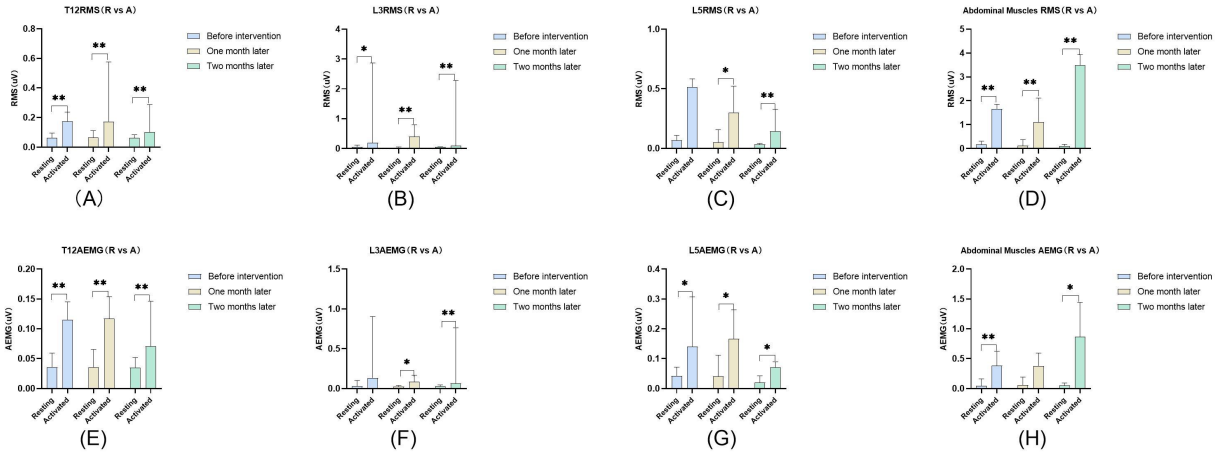


**Figure 3** Comparison of RMS and AEMG between Resting and Activated States for T12, L3, L5, and Abdominal Muscles in the Experimental Group: (A)-(D) Represent the RMS of T12, L3, L5, and Abdominal Muscles Respectively in the Experimental Group under Resting and Activated States; (E)-(H) Represent the AEMG of T12, L3, L5, and Abdominal Muscles Respectively in the Experimental Group under Resting and Activated States
Note: *P < 0.05; **P < 0.01.

(2) Control Group: RMS and AEMG (RV vs. AV)

As shown in Figure 4, the AV of T12 RMS, L3 RMS, and L3 AEMG at the paravertebral muscles were significantly higher than RV in three assessments ($P < 0.05$). For T12 AEMG, AV was significantly higher than RV at the baseline and one month after the intervention ($P < 0.05$). We also observed that the AV of L5 RMS and L5 AEMG at the paravertebral muscles were significantly higher than RV at the baseline and two months after the intervention ($P < 0.05$). Furthermore, the AV of abdominal muscle RMS and AEMG were significantly higher than RV in the assessment two months after the intervention ($P < 0.05$).

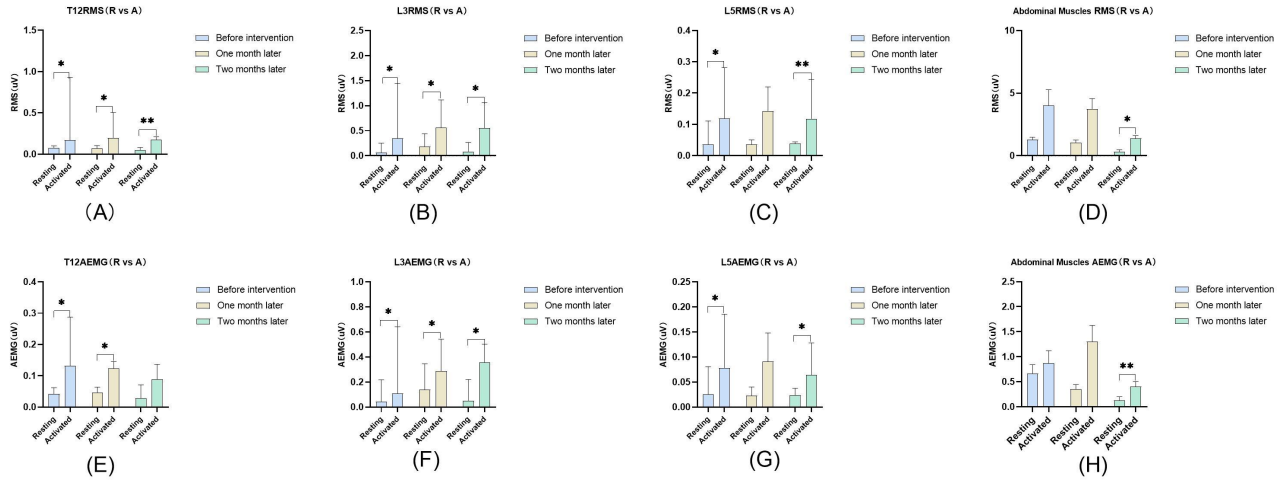


**Figure 4** Comparison of RMS and AEMG between Resting and Activated States for T12, L3, L5, and Abdominal Muscles in the Control Group: (A)-(D) Represent the RMS of T12, L3, L5, and Abdominal Muscles Respectively in the Control Group under Resting and Activated States; (E)-(H) Represent the AEMG of T12, L3, L5, and Abdominal Muscles Respectively in the Control Group under Resting and Activated States
Note: *P < 0.05; **P < 0.01.

(3) Between-Group Comparison of Activated State

As shown in Figure 5 (A) - (B), the AV of abdominal RMS and AEMG were significantly higher in the experimental group than the control group at 8 weeks ($P < 0.05$). We can see AV of abdominal AEMG was significantly higher in the control group at 4 weeks ($P < 0.05$) but significantly higher in the experimental group at 8 weeks ($P < 0.05$), showing a significant increasing trend in the experimental group.

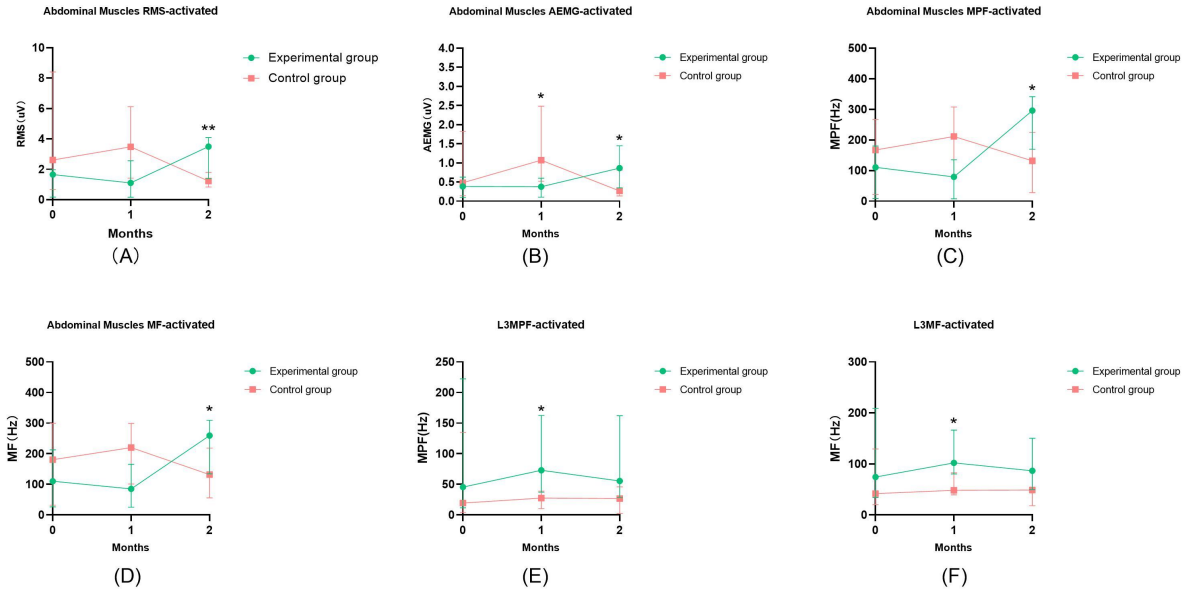


**Figure 5** Comparison of Activated States between the Experimental Group and the Control Group: (A)-(D) Represent the RMS, AEMG, MPF, and MF of the Abdominal Muscles Respectively in both Groups under the Activated State Respectively; (E)-(F) Represent the MPF and MF of L3 Respectively in Both Groups under the Activated State
Note: *P < 0.05; **P < 0.01.

### *3.2.2 Muscle fatigue tolerance*

(1) Experimental Group: MPF and MF (RV vs. AV)

As shown in Table 2, the AV of L3 MPF and MF at the paravertebral muscles were significantly higher than RV at 4 weeks (P < 0.05), but not significantly different at 8 weeks. The AV of abdominal MPF and MF were significantly higher RV at all three assessments (P < 0.05).

**Table 2** Comparison of MPF and MF between Resting and Activated States in the Experimental Group

| Experimental group | Before intervention | | | | One month later | | | | Two months later | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Indicator | Resting | Activated | t/z | P | Resting | Activated | t/z | P | Resting | Activated | t/z | P |
| T12-MPF | 28.798±5.774 | 30.689 (14.627,37.084) | 0.059 | 0.953 | 28.613 (28.024,32.071) | 35.838 (22.427, 139.264) | 1.481 | 0.139 | 31.312 (28.728,32.426) | 31.698(29.039,47.282) | 1.244 | 0.214 |
| L3-MPF | 27.557(4.532,31.396) | 107.524±103.861 | 1.599 | 0.11 | 33.344±11.655 | 103.589 ±77.575 | 2.747 | 0.025 * | 31.219±9.853 | 55.550(31.976,128.610) | 1.955 | 0.051 |
| L5-MPF | 11.913（4.428,34.488） | 4.050(2.520,43.379) | 1.481 | 0.139 | 20.186（3.585,37.127） | 5.284 (2.978,31.500) | 0.889 | 0.374 | 36.617±20.205 | 44.161±39.814 | 0.458 | 0.659 |
| Abdominal Muscles-MPF | 24.341±7.218 | 105.921±103.622 | 2.351 | 0.047 * | 30.544（14.180, 37.672） | 79.575 (7.563,135.111) | 2.073 | 0.038 * | 33.073（29.238, 142.804） | 250.540±111.457 | 2.429 | 0.015 * |
| T12-MF | 159.041±145.47 | 57.489±30.807 | 0.721 | 0.492 | 194.173± 125.613 | 82.077± 56.966 | 1.859 | 0.1 | 129.566±106.651 | 49.929(47.553,88.250) | 1.125 | 0.26 |
| L3-MF | 42.942±25.358 | 123.029±92.967 | 2.077 | 0.071 | 63.701±13.895 | 121.902 ±66.476 | 2.603 | 0.031 * | 58.354±14.918 | 103.230±73.189 | 1.807 | 0.108 |
| L5-MF | 36.627 (20.747,63.896) | 18.481 (8.864,76.496) | 1.244 | 0.214 | 42.383±22.746 | 15.188 (6.568,56.684) | 1.244 | 0.214 | 58.792 (50.332,73.4110) | 68.268±35.398 | 0.059 | 0.953 |
| Abdominal Muscles-MF | 40.177±10.237 | 118.462±92.124 | 2.58 | 0.033 * | 44.780（32.556, 71.688） | 114.416 ±93.812 | 2.073 | 0.038 * | 44.544（43.115, 181.035） | 236.253±91.697 | 2.429 | 0.015 * |

(2) Control Group: MPF and MF (RV vs. AV)

As shown in Table 3, The AV of T12 MF at the paravertebral muscles was significantly higher than RV at 4 weeks ($P < 0.05$), but not significantly different at 8 weeks. Other indicators showed no statistical significance but an overall increasing trend, except AV of L5 MPF and MF, which were lower than RV.

**Table 3** Comparison of MPF and MF between Resting and Activated States in the Control Group

| Control group | Before intervention | | | | One month later | | | | Two months later | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Indicator | Resting | Activated | t/z | P | Resting | Activated | t/z | P | Resting | Activated | t/z | P |
| T12-MPF | 32.096±14.317 | 61.34±49.889 | 1.866 | 0.099 | 36.846 (30.985,37.254) | 100.06±86.132 | 1.955 | 0.051 | 30.530±4.801 | 41.950±25.854 | 1.415 | 0.195 |
| L3-MPF | 37.046 (17.491,37.482) | 19.578 (4.193,91.685) | 0.296 | 0.767 | 37.220 (36.879,38.150) | 27.504 (12.641,38.413) | 0.889 | 0.374 | 7.646(5.879,36.826) | 30.235±29.914 | 1.007 | 0.314 |
| L5-MPF | 34.335(18.904,36.996) | 20.467±17.909 | 1.125 | 0.26 | 33.366±15.657 | 27.613±19.943 | 1.042 | 0.328 | 31.305±18.402 | 8.408 (4.679,43.447) | 0.889 | 0.374 |
| Abdominal Muscles-MPF | 52.863(32.403,399.911) | 159.041±145.470 | 0.059 | 0.953 | 192.765±166.303 | 194.173±125.613 | 0.04 | 0.969 | 35.067 (23.142,82.616) | 129.566±106.651 | 1.718 | 0.086 |
| T12-MF | 47.546(41.591,66.026) | 86.270±65.959 | 0.652 | 0.515 | 56.964±11.879 | 115.030±80.192 | 2.358 | 0.046* | 45.991±6.298 | 61.349±27.848 | 1.912 | 0.092 |
| L3-MF | 42.110(32.554,89.950) | 41.758 (20.169,129.477) | 1.125 | 0.26 | 52.305 (48.593,77.780) | 60.782±35.669 | 0.889 | 0.374 | 33.593±16.365 | 52.581±36.203 | 1.674 | 0.133 |
| L5-MF | 54.07±28.545 | 41.363±20.561 | 1.271 | 0.239 | 67.467±24.288 | 54.038±27.103 | 1.777 | 0.113 | 56.131±27.079 | 39.647±23.434 | 1.815 | 0.107 |
| Abdominal Muscles-MF | 125.466 (52.975,350.649) | 172.642±113.066 | 0.059 | 0.282 | 188.312±146.348 | 195.888±99.122 | 0.228 | 0.825 | 52.669 (37.912,93.599) | 137.538±88.450 | 1.599 | 0.11 |

(3) Between-Group Comparison of Activated State

As shown in Figure 5 (C) - (F), the AV of abdominal MPF and MF were significantly higher in the experimental group than the control group at 8 weeks ($P < 0.05$). Additionally, the AV of L3 MPF and MF at the paravertebral muscles were significantly higher in the experimental group than the control group at 4 weeks ($P < 0.05$), with no significant difference later.

### 3.3 Clinical Outcome Assessments

#### *3.3.1 SCIM-III*

As shown in Table 4, between-group comparisons revealed significantly higher scores in the experimental group than the control group at both 4 weeks (t=2.599, P=0.019, Cohen'd=1.225, 95%CI=(0.194, 2.225)) and 8 weeks (t=2.815, P=0.012, Cohen'd=1.327, 95%CI=(0.280,2.341)). As presented in Table 4 and Figure 6(A), within-group comparisons showed highly significant improvements for the experimental group ($F=26.213$, $P < 0.001$, partial $\eta^2=0.766$) and the control group ($F=10.218$, $P=0.009$, partial $\eta^2=0.743$). Bonferroni-corrected pairwise comparisons of the two groups revealed significant differences: the experimental group: between 4 weeks and baseline ($P = 0.009$, 95%CI=(1.700, 10.077)), 8 weeks and baseline ($P = 0.001$, 95%CI=(4.956, 16.155)), 8 weeks and 4 weeks ($P = 0.005$, 95%CI=(1.609, 7.724)); the control group: between 4 weeks and baseline ($P = 0.011$, 95%CI=(0.572, 3.872)), 8 weeks and baseline ($P = 0.004$, 95%CI=(2.239, 9.761)), 8 weeks and 4 weeks ($P = 0.006$, 95%CI=(1.226, 6.330)). Two months post-intervention, both groups showed clinically meaningful improvements in SCIM-III scores (≥ MCID=4 points): 10.556-point increase in the experimental group and 6.000-point increase in the control group from baseline.

**Table 4** Comparison of Clinical Outcomes between Groups and Analysis of Variance for Repeated Measures within Groups of SCIM-III, WISCI, JOA

| SCIM-III | Experimental Group | Control Group | t | P | Cohen'd | 95%CI |
|---|---|---|---|---|---|---|
| Before intervention | 58.444±9.329 | 47.778±15.114 | 1.802 | 0.09 | 0.849 | (-0.132, 1.806) |
| One month later | 64.333±7.969 | 50.000±14.500 | 2.599 | 0.019* | 1.225 | (0.194, 2.225) |
| Two months later | 69.000±7.937 | 53.778±14.149 | 2.815 | 0.012* | 1.327 | (0.280, 2.341) |
| F | 26.213 | 10.128 | | | | |
| P | < 0.001*** | 0.009** | | | | |
| partial $\eta^2$ | 0.766 | 0.743 | | | | |
| WISCI | Experimental Group | Control Group | t/z | P | Cohen'd | 95%CI |
| Before intervention | 7.556±6.085 | 4.000(3.000,4.500) | 1.566 | 0.137 | 0.738 | (-0.231, 1.686) |

| | | | | | | |
|---|---|---|---|---|---|---|
| One month later | 8.667±5.723 | 5.000(3.500,7.000) | 1.434 | 0.171 | 0.676 | (-0.287, 1.619) |
| Two months later | 9.667±5.074 | 6.222±4.919 | 1.462 | 0.163 | 0.689 | (-0.275, 1.633) |
| F | 5.617 | 3.99 | | | | |
| P | 0.029* | 0.07 | | | | |
| partial $\eta^2$ | 0.412 | 0.533 | | | | |
| JOA | Experimental Group | Control Group | t | P | Cohen'd | 95%CI |
| Before intervention | 11.441±3.500 | 9.667±4.093 | 0.99 | 0.337 | 0.437 | (-0.478, 1.397) |
| One month later | 14.000±3.808 | 10.444±4.475 | 1.815 | 0.088 | 0.856 | (-0.126, 1.813) |
| Two months later | 16.222±3.527 | 12.222±4.738 | 2.032 | 0.059 | 0.958 | (-0.036, 1.925) |
| F | 115.75 | 29.263 | | | | |
| P | < 0.001*** | < 0.001*** | | | | |
| partial $\eta^2$ | 0.935 | 0.785 | | | | |

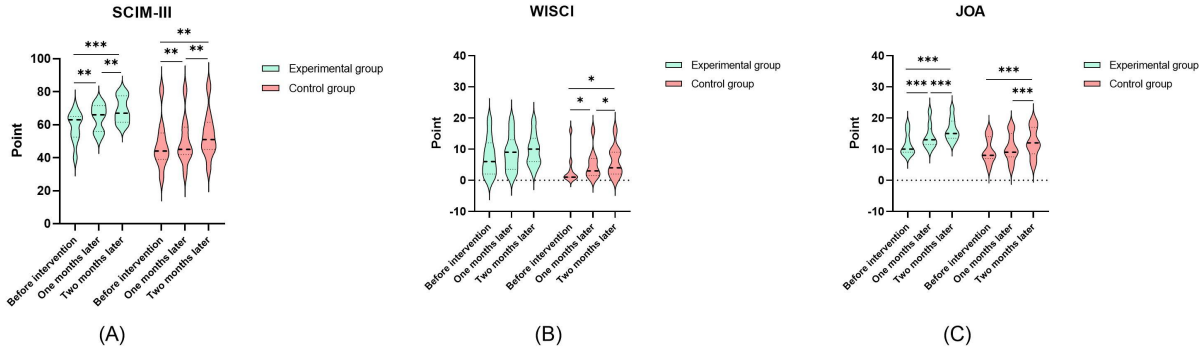


**Figure 6** Comparison of SCIM-III, WISCI, and JOA Scores between the Experimental Group and the Control Group at Three Time Points: (A)-(C) Represent the Comparison Results and Trends of SCIM-III, WISCI, and JOA Scores Respectively within Each of the Two Groups.
Note: *P < 0.05; **P < 0.01; ***P < 0.001.

### *3.3.2 WISCI*

As shown in Table 4, between-group comparisons showed no significant differences at any time point. As shown in Table 4 and Figure 6(B), within-group comparison for the experimental group showed statistical significance($F=5.617$, $P=0.029$, partial $\eta^2=0.412$). But Bonferroni-corrected pairwise comparisons of the experimental group revealed no significant differences, between 4 weeks and baseline ($P = 0.352$, 95%CI=(-0.799, 3.021)), 8 weeks and baseline ($P = 0.085$, 95%CI=(-0.270, 4.492)), 8 weeks and 4 weeks ($P = 0.120$, 95%CI=(-0.231, 2.231)). Within-group comparison for the control group showed no significant improvements ($F=3.99$, $P=0.07$, partial $\eta^2=0.533$). Bonferroni-corrected pairwise comparisons of the control group revealed no significant differences, between 4 weeks and baseline ($P = 0.050$, 95%CI=(0.000, 3.334)), 8 weeks and baseline ($P = 0.051$, 95%CI=(-0.011, 5.566)), as well as 8 weeks and 4 weeks ($P = 0.064$, 95%CI=(-0.062, 2.284)). Two months post-intervention, both groups showed clinically meaningful improvements in WISCI scores (≥ MCID=2 points): Since the distribution patterns of the experimental group data were not consistent, the median was used to describe the magnitude of improvement: the median WISCI-II score in the experimental group increased from 4.00 before the intervention to 10 at 8 weeks of intervention, exceeding the MCID. 2.778-point increase in the control group from baseline.

### *3.3.3 JOA*

As shown in Table 4, between-group comparisons showed no significant differences. As shown in Table 4 and Figure 6(C), within-group comparisons showed highly significant improvements for both groups. The experimental group ($F=115.75$, $P < 0.001$, partial $\eta^2=0.935$) and the control group ($F=29.263$, $P< 0.001$, partial $\eta^2=0.785$). Bonferroni-corrected pairwise comparisons of the two groups revealed significant differences: the experimental group: between 4 weeks and baseline ($P < 0.001$, MCID=2.556, 95%CI=(1.536, 3.575)), 8 weeks and baseline ($P < 0.001$, MCID=4.778, 95%CI=(3.801, 5.755)), 8 weeks and 4 weeks ($P < 0.001$, MCID=2.222, 95%CI=(1.385, 3.060)); the control group: between 8 weeks and baseline ($P = 0.001$, MCID=2.556, 95%CI=(1.215, 3.896)), as well as 8 weeks and 4 weeks ($P < 0.001$, MCID=1.778, 95%CI=(0.940, 2.615)). Two months post-intervention, both groups showed clinically meaningful improvements in JOA scores (≥MCID=2.5 points): 4.778-point increase in the experimental group and 2.556-point increase in the control group from baseline.

## 3.4 Safety Indicators

Five participants in the experimental group reported mild adverse events: transient upper limb muscle soreness (n=3), mild lumbar fatigue (n=1), and neck skin redness (n=1), all resolving after rest. Four participants in the control group reported mild adverse events: mild lumbar soreness (n=2), mild abdominal soreness (n=1), and mild neck/shoulder discomfort (n=1), all resolving after rest. No moderate or severe adverse events occurred in either group. Adverse event incidence showed no significant difference between groups, indicating good safety for both training methods.

### 3.5 Satisfaction Survey

3.5.1. Device Training Group (n=20)
n=16 (80%) found the trainer simple and convenient to use. n=13 (65%) reported good therapeutic effects, particularly for upper limb and back core muscle strength. n=17 (85%) appreciated the convenience of training in seated or standing positions without posture restrictions.
3.5.2. Bridge Exercise Group (n=20)
n=12 (60%) found the exercise simple but requiring family assistance. n=15 (75%) believed it effectively activated core muscles (back/abdominal). n=18 (90%) felt restricted by posture and location requirements.

## 4 DISCUSSION

This assessor-blinded randomized controlled trial enrolled 40 SCI subjects to compare the efficacy of a self-developed thoracolumbar active resistance rehabilitation trainer with traditional bridge exercises. The primary focus was to evaluate how these two interventions impact patients' functional independence, walking ability, and lumbar dysfunction, aiming to explore novel directions for SCI rehabilitation clinical practice.
Both training methods significantly activated sEMG parameters of lumbar and abdominal muscles, but there were notable differences in core efficacy. In terms of motor unit recruitment capacity—a key indicator of muscle activation intensity—the experimental group showed significantly higher AV of RMS and AEMG at T12 paravertebral muscles, as well as RMS at L3 and abdominal regions, and AEMG at L5, compared to baseline (RV). Importantly, the activation effect of abdominal AEMG gradually enhanced with prolonged training, indicating progressive improvement in muscle engagement. In contrast, the control group mainly effectively activated L3 paravertebral muscles and T12 RMS, with delayed activation of L5 paravertebral muscles. Intergroup comparisons at the 8-week mark revealed that the experimental group had significantly higher abdominal RMS and AEMG AV than the control group, demonstrating the trainer's superior ability to recruit core muscles. This finding aligns with previous research [19], which reported that integrated EMG correlates positively with muscle force and tension, confirming the clinical relevance of the sEMG results.
Regarding fatigue tolerance—another critical metric for evaluating long-term muscle function—the experimental group exhibited significantly higher AV of abdominal MPF and MF than RV at all measurement time points, indicating the trainer could effectively enhance the fatigue resistance of abdominal muscles, a key component of core stability. The control group, however, only showed improvements in MPF and MF of L3 paravertebral muscles at 4 weeks, with no significant effect at 8 weeks, suggesting that bridge exercises have limited and unsustainable efficacy in improving paravertebral muscle fatigue resistance. This study showed that the trainer had advantages in improving the fatigue resistance of L3 paravertebral muscles in the early stage and enhancing abdominal fatigue resistance in the later stage.
Mechanistically, the two methods differ substantially in force generation. When using the trainer, the experimental group relied on active force exertion of spinal middle muscles to maintain stability, with back muscles recruiting a sufficient number of motor units to perform isometric contractions. Given that the well-developed muscle bellies of the erector spinae and multifidus muscles are concentrated in the T10-L5 segment, T12 paravertebral muscles (close to the spinal midsection) were easily fully activated, and other core muscles were also partially activated. In contrast, bridge exercises require core muscles to act as the hub to achieve the linkage of hip joint extension and trunk hyperextension [20]. As a key force-generating point in the lumbar midsegment, L3 was fully activated, while other muscles were only synchronously partially activated. This mechanistic discussion is consistent with previous studies: although anterior and posterior trunk muscles are anatomical antagonists, they functionally synergize to maintain balance [21]; strengthening posterior trunk muscles and maintaining their dominance over anterior muscles during rehabilitation helps improve poor alignment in SCI patients and enhance overall spinal stability [22].
Clinically, both training methods improved SCI patients' independence and reached the minimal clinically important difference (MCID), with the trainer group significantly superior to the bridge exercise group. This advantage is closely related to the enhanced core stability achieved by the coordinated activation of upper limb, back, and abdominal muscles in the experimental group, consistent with previous research conclusions that exoskeleton gait training improves patients' independence [23]. Regarding walking ability and lumbar function, although there was no significant intergroup difference, both groups reached MCID post-intervention compared to pre-intervention, indicating continuous training can promote clinical improvements in these aspects. We speculate this is related to improved core stability enhancing balance ability [24-25], providing preliminary exploratory evidence for the correlation between core stability and walking function in SCI patients.
In terms of safety, no moderate or severe adverse events occurred during training, and mild adverse events resolved within one day, confirming good safety of both methods. Subjective evaluations showed 85% of trainer users considered it easy to operate, portable, wheelchair-compatible, and capable of simultaneous upper limb training; 90% of bridge exercise users reported restrictions by posture and location, often requiring assistance, highlighting the trainer's convenience advantage for home and community rehabilitation.
Despite the non-negligible clinical effects, this study has limitations. First, its results involve the superimposed effect of conventional rehabilitation training on the two interventions, though both groups received such training to minimize this impact. Second, during sEMG signal collection, core muscles were treated as a whole, with only paravertebral and paraumbilical muscles measured, insufficient to fully capture deep core muscle signals. Third, the exploratory scope is superficial, focusing only on biomechanical and clinical rehabilitation perspectives for mechanistic discussion.

## 5 CONCLUSION

Both the thoracolumbar active resistance rehabilitation trainer and traditional bridge exercise are clinically meaningful for improving the independence, walking ability, and lumbar function of patients with SCI. However, the thoracolumbar active resistance rehabilitation trainer demonstrates significantly superior effectiveness in enhancing spinal cord independence compared to traditional bridge training. This device exhibits high safety and a broad scope of application, offering a superior choice for the clinical rehabilitation of SCI patients.

## COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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