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Effect of Rehabilitation Training Based on Digital Treadmill on Walking Ability of Patients with Incomplete Spinal Cord Injury

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Abstract

Objective: To explore the effects of rehabilitation training based on digital treadmill on walking ability of patients with incomplete spinal cord injury. **Methods:** 93 patients with incomplete spinal cord injury admitted to our hospital from November 2020 to September 2022 were retrospectively analyzed and divided into control group (n = 46) and treatment group (n = 47) according to treatment methods. The control group received pure rehabilitation training; The treatment group received rehabilitation training based on digital treadmill. Lower limb muscle strength, walking ability, gait parameters and daily living ability were compared between the two groups. **Results:** After treatment, quadriceps muscle strength, 10 m walking time, 6min walking endurance test distance, LEMS score, step length, step speed, step frequency, maximum knee flexion Angle, maximum hip flexion Angle, MBI score and FIM score in both groups were improved compared with those before treatment (p < 0.05). After treatment, quadriceps muscle strength, 10m walking time [(41.16 ± 16.66) s], 6 min walking endurance test distance [(43.14 ± 12.59) m], LEMS score [(41.15 ± 3.68) min], step length [(48.85 ± 9.44) cm], step speed [(0.45 ± 0.03) M/s), stride frequency step (62.49 + 6.19)/minutes, knee flexion Angle [(67.21-6.84)°], hip flexion Angle [(45.32 - 5.27)°], MBI score [(71.09 - 18.08)], FIM score [(111.23 - 7.24)] The improvement was better than that of control group (p < 0.05). **Conclusions:** Compared with simple rehabilitation training, rehabilitation training based on digital treadmill can improve lower limb muscle strength, walking ability and gait parameters of patients with incomplete spinal cord injury, and is conducive to improving patients' daily living ability.

1 Introduction

Incomplete spinal cord injury (iSCI) represents a severely disabling condition characterized by impaired ambulation, sensory deficits, and autonomic dysfunction below the injury level, significantly compromising patients' activities of daily living [1]. Conventional rehabilitation approaches such as functional electrical stimulation and body-weight-supported treadmill training demonstrate limited efficacy in fully restoring ambulatory capacity and lower limb muscle strength [2]. Digital treadmill systems utilize anti-interference high-speed 3D infrared cameras to capture real-time gait parameters during training, providing immediate visual and auditory feedback through display interfaces to enhance locomotor function rehabilitation [3]. Emerging as a promising neurorehabilitation tool, digital treadmill training has shown efficacy in improving gait performance and balance control in stroke patients [4], though its application in iSCI remains underexplored. This study investigates the therapeutic effects of digital treadmill training on ambulatory function in iSCI patients, aiming to establish novel rehabilitation strategies for this population.

2 Materials and methods

2.1 Research objects

Inclusion criteria were: (1) meeting the American Spinal Injury Association (ASIA) Impairment Scale grade C or D with lower limb dysfunction [5]; (2) spinal cord injury levels between T_6 and L_1; (3) disease duration within 6 months; and (4) signed informed consent from all patients or guardians. Exclusion criteria comprised: (1) patients with severe cognitive impairment; (2) those with poor compliance; and (3) individuals with comorbidities affecting ambulatory function.

A total of 93 patients with incomplete spinal cord injury admitted to Ningbo Rehabilitation Hospital from November 2020 to September 2022 were enrolled as study subjects and randomly divided into a control group (n = 46) and a treatment group (n = 47) using a random number table. No statistically significant differences ($p > 0.05$) were observed between the two groups in baseline characteristics including gender, age, time from spinal cord injury to initiation of rehabilitation training, and ASIA classification, indicating comparability (Table 1). This study was approved by the Ethics Committee of Ningbo Rehabilitation Hospital [Approval No. (2020) Ethical Review (Scientific Research 006)].

Table 1 General information of the two groups of patients.

Group	Cases	Gender (cases)		Age (years, mean± standard deviation)	Time from spinal cord injury to rehabilitation training (month, mean ± standard deviation)	ASIA grading (cases)	
		Male	Female			Level C	Level D
Control group	46	30	16	54.72 ± 14.30	0.85 ± 0.70	17	29
Treatment group	47	32	15	58.19 ± 14.82	0.96 ± 0.88	17	30

2.2 Intervention methods

Both groups received conventional rehabilitation training while wearing thoracolumbar braces, with training protocols adjusted according to rehabilitation phases and progress. Specific interventions included: ① During absolute bed rest, the bed head was gradually elevated based on spinal stability to facilitate postural transition from supine to semi-recumbent and sitting positions; patients performed respiratory training (diaphragmatic breathing, exhalation exercises, pursed-lip breathing) to enhance diaphragmatic movement; active/passive joint exercises were implemented alongside bladder function training (controlled voiding volume 300-500 mL) as appropriate. ② In the rehabilitation phase, seated balance training was initiated with abdominal muscle activation (head/shoulder lifts during exhalation, gradual return during inhalation), followed by lower limb elevation and bridge exercises (30 min/session, 5 days/week). ③ Progressive dynamic balance training was introduced according to residual muscle strength, beginning with parallel bar standing/walking (20 min/session) with gradual duration extension, then advancing to walking aids. All training protocols were maintained for 3 months.

The treatment group received additional digital treadmill-based rehabilitation training (Walkerview 3.0, TecnoBody, Italy) alongside conventional therapy. During training sessions, therapists assisted patients in standing on the treadmill while attaching the emergency stop clip to their clothing, which automatically activated safety mechanisms in case of falls or detachment. Prior to initial treatment, gait analysis was performed by selecting the "Gait Training" mode to determine individualized parameters including walking speed, stride length, and hip/knee joint angles for the affected side. Therapists and family members provided bilateral support during 20-minute training sessions (once daily, 5 days/week for 3 months) to prevent falls.

2.3 Evaluation method of therapeutic effect

The quadriceps muscle strength and walking ability of the two groups of patients were evaluated before treatment and 3 months after treatment, and gait parameters were collected to calculate the maximum knee flexion Angle and hip flexion Angle, and the daily living activities ability was evaluated.

2.3.1 Quadriceps Strength

Quadriceps muscle strength was assessed using the Lovett scale (Grades 0-5), where Grade 0 indicated no detectable muscle contraction; Grade 1 represented slight skin flickering without joint muscle contraction activity; Grade 2 denoted horizontal limb movement on the bed surface without gravity resistance; Grade 3 signified antigravity movement without resistance; Grade 4 indicated movement against moderate (but not full) resistance; and Grade 5 represented normal strength against full resistance [6].

2.3.2 Walking ability

The walking ability of the two groups was determined by 10 m walking time, 6 min walking endurance and lower limb movement score (lower limb motor score, LEMS). The details were as follows: ① The 10-meter walk test, performed with a 3D gait analysis system where patients walked 14 m in a straight line at their fastest sustainable speed to eliminate acceleration/deceleration effects, with the central 10m timed and averaged across three trials (5-minute rest intervals); ② The 6-minute walk test, recording the maximum distance covered during encouraged but self-paced ambulation. During the test, if the patient cannot persist due to fatigue, he can stop and rest in the middle, and the therapist can give the patient timely encouragement and guidance; ③ The Lower Extremity Motor Score (LEMS, 50-point scale) assessing hip flexors, knee extensors, ankle dorsiflexors/plantarflexors, and hallux extensors, with higher scores indicating better function [7].

2.3.3 Gait parameters

Patients wearing ink-marked shoes walked along a 10-meter paper walkway, with the initial and final 2-meter segments excluded to ensure measurement stability. Temporal parameters were recorded using a digital stopwatch. Step length was calculated as the mean longitudinal distance between consecutive heel strikes during the central 6-meter segment, while walking speed = total distance/travel time, and cadence was measured as steps per minute [8]. Spatial-temporal, kinematic, and kinetic data were acquired using the Dutch CAREN system (Computer Assisted Rehabilitation Environment), integrating infrared cameras and force plates to compute maximum knee and hip flexion angles during ambulation.

2.3.4 Activities of daily living (ADL)

ADL were assessed using both the Modified Barthel Index (MBI, total score 100 points) [9] and Functional Independence Measure (FIM) [2], with the MBI evaluating self-care domains including feeding, toileting, and continence (higher scores indicating greater independence), while the FIM quantified functional independence levels (improved scores reflecting enhanced autonomy).

2.4 Statistical analysis

Statistical analysis was performed using SPSS version 20.0, with count data compared by χ^2 test and the measurement data were expressed as the mean ± standard deviation. The independent sample *t*-test was used to compare the two groups, while paired sample *t*-test was used for comparison before and after treatment., with statistical significance set at $p < 0.05$.

3 Results

3.1 Comparison of quadriceps muscle strength before and after treatment in two groups of patients

Before treatment, there was no statistically significant difference in quadriceps muscle strength between the two groups ($p > 0.05$). After treatment, the quadriceps muscle strength of both groups improved compared to before treatment ($p < 0.05$), with the treatment group showing better improvement than the control group ($p < 0.05$, Table 2).

Table 2 Comparison of quadriceps muscle strength before and after treatment in two groups of patients (cases).

Group		Cases	Lovett muscle Strength grades 0 to 5					
			Grade 0	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Control group	Before treatment	46	16	3	7	18	1	0
	After treatment	46	1	6	4	8	23	3 [a]
Treatment group	Before treatment	47	12	7	4	17	7	0
	After treatment	47	0	0	2	12	21	12 [ab]

Note: Compared with the before treatment group, [a] $p < 0.05$; compared with the after treatment group, [b] $p < 0.05$.

3.2 Comparison of walking ability before and after treatment between the two groups of patients

Before treatment, no significant intergroup differences were observed in 10-meter walk time, 6-minute walk distance, or LEMS scores ($p > 0.05$). Following treatment, both groups exhibited significant improvements, with reduced 10 m walk times and increased 6-minute walk distances and LEMS scores ($p < 0.05$), though the treatment group demonstrated superior improvements in all three parameters compared to controls ($p < 0.05$, Table 3).

Table 3 Comparison of walking ability before and after treatment between the two groups of patients (mean ± standard deviation).

Group		Cases	10 m walking time test (s)	6 min walking endurance test (m)	LEMS (scores)
Control group	Before treatment	46	98.31 ± 25.87	16.52 ± 11.24	10.33 ± 5.03
	After treatment	46	56.06 ± 16.86 [a]	34.47 ± 10.20 [a]	29.83 ± 3.50[a]
Treatment group	Before treatment	47	99.64 ± 26.17	16.85 ± 8.76	10.49 ± 5.30
	After treatment	47	41.16 ± 16.66 [ab]	43.14 ± 12.59 [ab]	41.15 ± 3.68 [ab]

Note: Compared with the before treatment group, [a] $p < 0.05$; compared with the after treatment group, [b] $p < 0.05$.

3.3 Comparison of gait parameters before and after treatment in two groups of patients

Before treatment, there was no significant difference between the two groups in step length, walking speed, cadence, maximum knee flexion angle, or maximum hip flexion angle ($p > 0.05$). After treatment, the above indicators of both groups of patients were improved compared with those before the treatment within the groups ($p < 0.05$), with the treatment group achieving significantly greater enhancements in all measured kinematic variables compared to controls ($p < 0.05$, Table 4 and Table 5).

Table 4 Comparison of gait parameters before and after treatment in two groups of patients (mean ± standard deviation).

Group		Cases	Step (cm)	Leg speed (m/s)	Step frequency (steps/min)
Control group	Before treatment	46	30.00 ± 2.51	0.14 ± 0.03	22.63 ± 4.95
	After treatment	46	43.13 ± 7.36 [a]	0.32 ± 0.03 [a]	50.07 ± 5.71 [a]
Treatment group	Before treatment	47	29.38 ± 4.04	0.13±0.03	20.66 ± 5.86
	After treatment	47	48.85 ± 9.44 [ab]	0.45 ± 0.03 [ab]	62.49 ± 6.19 [ab]

Note: Compared with the before treatment group, [a] $p < 0.05$; compared with the after treatment group, [b] $p < 0.05$.

Table 5 Comparison of exercise parameters before and after treatment in two groups of patients (°, mean ± standard deviation).

Group		Cases	Maximum knee flexion Angle	Maximum hip flexion Angle
Control group	Before treatment	46	50.61 ± 5.99	34.22 ± 3.54
	After treatment	46	59.26 ± 6.34 [a]	41.80 ± 3.67 [a]
Treatment group	Before treatment	47	51.85 ± 5.92	34.60 ± 3.40
	After treatment	47	67.21 ± 6.84 [ab]	45.32 ± 5.27 [ab]

Note: Compared with the before treatment group, [a] $p < 0.05$; compared with the after treatment group, [b] $p < 0.05$.

3.4. Comparison of daily living activities before and after treatment between the two groups of patients

Before treatment, there was no statistically significant difference in the MBI score and FIM score between the two groups ($p > 0.05$). After treatment, both groups demonstrated significant increases in MBI and FIM scores compared to their respective pretreatment values ($p < 0.05$), with the treatment group achieving significantly higher post-treatment scores on both measures relative to the control group ($p < 0.05$, Table 6).

Table 6 Comparison of daily living activities before and after treatment in two groups of patients (scores, mean ± standard deviation).

Group		Cases	MBI	FIM
Control group	Before treatment	46	38.25 ± 17.60	80.35 ± 10.38
	After treatment	46	61.76 ± 17.25 ^{a}	100.11 ± 3.15 ^{a}
Treatment group	Before treatment	47	40.14 ± 20.45	78.02 ± 12.87
	After treatment	47	71.09 ± 18.08 ^{ab}	111.23 ± 7.24 ^{ab}

Note: Compared with the before treatment group, $^{a}p < 0.05$; compared with the after treatment group, $^{b}p < 0.05$.

4 Discussion

Clinical practice often utilizes assistive devices to restore ambulation in spinal cord injury patients, though such assisted walking may compromise stability and induce abnormal gait patterns [10]. Previous studies have demonstrated correlations between specific muscle strength and walking capacity, with early recovery of muscular strength serving as a predictive indicator for functional ambulation in incomplete spinal cord injury [8]. Our findings revealed that both groups exhibited post-treatment improvement in muscle strength compared to before treatment, with the treatment group demonstrating superior gains versus controls. Compared to before treatment, significant enhancements were observed in 6-minute walk distance, LEMS scores, step length, walking speed, cadence, maximum knee/hip flexion angles, MBI and FIM scores for both groups post-treatment, with the treatment group showing greater improvements across all parameters. Additionally, 10-meter walk times decreased significantly in both groups after treatment, with the treatment group achieving shorter times than controls. These results collectively indicate that the integration of digital treadmill-based training with conventional rehabilitation yields superior outcomes in lower extremity strength, ambulatory capacity, gait parameters, and activities of daily living compared to standard rehabilitation alone in patients with incomplete spinal cord injury.

In conventional rehabilitation, functional electrical stimulation involves placing electrodes over major lower extremity muscle groups to induce changes in ion permeability across cell membranes, thereby generating action potentials that counteract disuse atrophy and improve muscle strength [11]. Similarly, body-weight-supported treadmill training promotes symmetrical weight distribution during gait rehabilitation, facilitating the reacquisition of normal walking patterns and ultimately enhancing functional ambulation for improved activities of daily living [12].

The digital running track represents an advanced iteration of conventional treadmills, adding an anti-interference high-speed infrared camera system that precisely captures real-time angular changes across all joints during training. Coupled with sensitive pressure sensors, it dynamically records gait parameters (e.g., step length) and provides visual feedback via display to facilitate abnormal gait correction, enabling patients to perform ambulatory training with near-normal gait patterns. Xiao et al [13] demonstrated the digital treadmill has a good retest reliability for spatio-temporal parameters such as the average value of trunk flexion and extension, the average value of trunk scoliosis, the range of motion of trunk scoliosis joints, and the range of motion of flexion and extension joints of both hip joints obtained from gait analysis. It can objectively reflect the walking function of normal people and can be used as an effective assessment tool for gait. Clinicians can program gait parameters slightly beyond patients' current capabilities, with auditory alerts providing feedback to help the patient gradually adjust the gait parameters when performance deviates from targets. Furthermore, the moving belt actively drives hip flexor activation, thereby enhancing muscle strength [14,15].

This study has several limitations, including a relatively small sample size and short observation period, which may introduce some degree of bias in the results; therefore, future research will focus on optimizing the experimental design, expanding the sample size, and extending the follow-up duration to further validate the effects of digital treadmill-based rehabilitation training on walking ability in patients with incomplete spinal cord injury, thereby providing a stronger theoretical foundation for evidence-based clinical interventions.

In conclusion, on the basis of simple rehabilitation training, supplemented by rehabilitation training based on digital running platforms can better improve the lower limb muscle strength, walking ability and gait parameters of patients with incomplete spinal cord injury, which is conducive to enhancing the patients' activities of daily living.

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Not applicable.

Conflicts of Interest

All authors declare that the research was conducted in the absence of any commercial or fnancial relationships that could be construed as a potential confict of interest.

Author Contributions

Conceptualization, Z.S.; Data curation, X.L.; Formal analysis, D.T.; Methodology, N.Q.; Writing-original draft, Q.F.; Writing-review and editing, Z.S.; All authors have read and agreed to the published version of the manuscript.

Ethics Approval and Consent to Participate

This study was approved by the Ethics Committee of Ningbo Rehabilitation Hospital [Approval No. (2020) Ethical Review (Scientific Research 006)].

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Availability of Data and Materials

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding authors.

Supplementary Materials

Not applicable.

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