ORIGINAL ARTICLE - PERIPHERAL NERVES

Combined selective peripheral neurotomy in the treatment of spastic lower limbs of spinal cord injury patients

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Abstract

Objective To explore the therapeutic effect of combined selective peripheral neurotomy (cSPN) on the spasm of the lower limbs after spinal cord injury.

Methods A prospective intervention (before-after trial) with an observational design was conducted in 14 spinal cord injury patients with severe lower limbs spasticity by cSPN. Given the severe spasm of hip adductor, triceps surae, and hamstring muscles in these patients, a total of 26 obturator nerve branches, 26 tibia nerve branches, and 4 sciatic nerve branches partial neurotomy were performed. The modified Ashworth scale, composite spasticity scale, surface electromyography, gait analysis, functional ambulation category, spinal cord independence measure, and modified spinal cord injury–spasticity evaluation tool were used before and after surgery.

Results Compared with preoperative, the spasm of the hip adductor, triceps surae, and hamstrings of the lower limbs in the postoperative patients decreased significantly. The abnormal gait of knee flexion and varus in the standing stage were significantly reduced. The grading of walking ability and activities of daily living were significantly improved.

Conclusions Combined selective peripheral neurotomy can significantly reduce the spasm of lower limbs post spinal cord injury, improve abnormal gait, and improve motor function and activities of daily living.

Trial registration ChiCTR1800019003 (2018–10-20).

Abbreviations

SPR	Selective posterior rhizotomy
SPN	Selective peripheral neurotomy
MAS	Modified Ashworth scale
CSS	Composite spasticity scale
FAC	Functional ambulation category
SCIM	Spinal cord independence measure
mSCI-SET	Modified spinal cord injury–spasticity evaluation tool
sEMG	Surface electromyography
ASIA	American Spinal Injury Association impairment scale

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Introduction

Spasticity and a spastic state are some of the common chronic complications of spinal cord injury, and these complications are characterized by increased muscle tension, hyperreflexia, clonus, and myotonia. Within 6–12 months after spinal cord injury, about approximately 70% of patients exhibit different degrees of limb spasm [16]. Although moderate spasms can delay muscle atrophy, maintain joint stability, and prevent venous thrombosis of the lower limbs, studies have shown that 27–40% of patients believe that spasticity will limit their ability to perform daily living activities. Spasticity manifests as limb stiffness, disturbed

sleep, spastic pain, movement, and walking disorders, and severe cases can lead to paralytic spasticity, affecting the rehabilitation effect and quality of life [1, 10, 15].

At present, the common treatment methods of spasm include exercise therapy, physiotherapy (functional electrical stimulation, EMG biofeedback, hydrotherapy, etc.), drug therapy (baclofen, tizanidine, diazepam, etc.), and nerve blockade therapy. However, most of these methods only aid in the temporary relief of muscle spasms, and studies have shown that 40% of spasm patients cannot tolerate the side effects of antispasmodic drugs [15]. Although botulinum toxin type A injection has the highest level of evidence and the largest range of indications, its effect is reversible, and it is often ineffective for severe spasms due to the effects of injection dose, muscle volume, and resistance after repeated injections [9, 26]. Surgery may be considered when the above treatments are ineffective [19].

Current surgical methods for spasm relief include spinal myelotomy, selective posterior rhizotomy (SPR), selective peripheral neurotomy (SPN), and corresponding orthopedic surgery. Myelotomy is currently only used in patients with severe refractory spastic paralysis with complete or near-complete spinal cord injury due to its many serious complications. The safety and efficacy of SPR surgery in the treatment of spastic cerebral palsy have been widely accepted, but the operation is more traumatic. In addition, complications, such as hypotonia, muscle weakness, sensory loss, and bladder dysfunction, often occur after surgery. SPN surgery has fewer postoperative complications, does not affect skin sensory function, and is safer [22].

At present, SPN surgery has been applied to the treatment of limb spasms in children with cerebral palsy and poststroke patients. The use of SPN surgery for limb spasm after spinal cord injury is rarely studied and mostly focuses on unilateral neurotomy of the muscular branch for spasm relief, and research reports on combined SPN (cSPN) surgery in the treatment of spasm after spinal cord injury are limited [8, 13, 20]. In this study, we intended to observe the efficacy of cSPN surgery in the treatment of severe lower limb spasms after spinal cord injury.

Methods and materials

Study population

Patients with spinal cord injury admitted to our department from July 2018 to October 2021 were selected to be evaluated by the same spasticity group surgeon for surgical indication. A total of 17 patients were prospectively selected for cSPN surgery. Functional assessment and outcome observation were performed before and after the surgery.

Inclusion criteria were as follows: (1.) patients over 18 years of age suffering from the spasticity of bilateral lower limbs after spinal cord injury and already in the plateau stage, and the degree of spasticity had not changed in the recent 6 months; (2.) spasticity exhibited no significant improvement or recurred after conservative treatment (physical therapy, drugs, botulinum toxin injection, etc.), and daily life, such as nursing, wheelchair riding, standing, and walking, were severely limited; and (3.) modified Ashworth scale (MAS) ≥ grade 3 with or without lower limb deformity. The exclusion criteria were as follows: (1.) cognitive impairment; (2.) severe primary diseases or poor general body condition; and (3.) inability to cooperate with rehabilitation after surgery. Our institutional review board approved the study, and informed consent was obtained from all the patients.

Surgical technique

All surgeries were performed by the same team of senior surgeons. Patients underwent tracheal intubation with general anesthesia and did not use long-acting muscle relaxant drugs during surgery to reduce interference with intraoperative nerve electrical stimulation. Depending on the location and extent of the patient's preoperative spasm, the corresponding cSPN was performed. On the day after the operation, the patient started standing exercises and gradually began other rehabilitation training without the use of a cast or other fixation. Stitches were removed 2 weeks after the operation.

Obturator nerve SPN The patient was laid down in a supine position, and bilateral knee flexion and hip flexion were fixed by using an external fixation booth. A superficial longitudinal incision approximately 3 cm long was performed along the body of the adductor longus in the proximal part of the thigh. The anterior branch of the obturator nerve was exposed on the surface of the adductor brevis, and the posterior branch of the obturator nerve was exposed on the surface of the adductor magnus muscle. Confirmation of these motor nerve branches was performed with electrical stimulation. Branches were divided into several fascicles, and parts with a low threshold and strong excitability confirmed by electrical stimulation were resected. Distal and proximal stumps of the fascicle were coagulated to prevent axonal regeneration. To determine whether the section was sufficient (or not), the muscle responses to the proximal and distal nerve stimulations to the section were compared, and the decrease in muscular response was noted.

Tibial nerve SPN The patient was laid down in a prone position. The median transverse incision in the popliteal fossa was approximately 3 cm long. The skin, superficial, and deep fascia were incised, and the total trunk of the tibial

nerve was exposed. According to the specific conditions, the medial, lateral gastrocnemius, and soleus nerves were selectively exposed and confirmed using electrical stimulation as they emerged from the lateral edge of the tibial nerve trunk. Branches were divided into several fascicles, and parts with a low threshold and strong excitability confirmed by electrical stimulation were resected. Distal and proximal stumps of the fascicle were coagulated to prevent axonal regeneration. To determine whether the section was sufficient (or not), the muscle responses to the proximal and distal nerve stimulations to the section were compared, and the decrease in muscular response was noted.

Sciatic nerve SPN The patient was laid in a prone position. A 5-cm transverse incision was performed in the gluteal fold, centered on the groove between the ischium and the greater trochanter. The skin and shallow and deep fascia were incised layer by layer, and the biceps femoris, semitendinosus muscle, and semimembranosus muscle were identified. These muscles were separated and pulled to both sides. The sciatic nerve was exposed at the depth of the incision. The epineurium was incised, and the motor nerve branch innervated the hamstrings and was confirmed using electrical stimulation. Branches were divided into several fascicles, and parts with a low threshold and strong excitability confirmed by electrical stimulation were resected. Distal and proximal stumps of the fascicle were coagulated to prevent axonal regeneration. To determine whether the section was sufficient (or not), the muscle responses to the proximal and distal nerve stimulations to the section were compared, and the decrease in muscular response was appreciated.

Evaluation

An evaluation was performed before the operation and 45 days after the operation using the MAS [6], composite spasticity scale (CSS) [17], functional ambulation category (FAC) [14], spinal cord independence measure (SCIM) [12], and modified spinal cord injury–spasticity evaluation tool (mSCI-SET) [2]. Surface electromyography (sEMG) and gait analysis were completed on the same day as the clinical evaluation. Both sEMG and gait analyzers were obtained from NORAXON (USA) and the data were analyzed using the MR33.8.6 system.

The surface electromyography test was conducted in the sEMG room of the China Rehabilitation Research Center and was performed by professional physicians. Adductor muscle electrical signals were collected during passive abduction of the hip joint. The electrical signals of the medial cephalic muscle of the gastrocnemius muscle were collected during passive dorsiflexion of the ankle joint, and the electrical signals of the hamstring muscles were obtained when the knee is passively straightened.

The gait analyzer recorded the real-time plantar pressure distribution and motor posture distribution. The system data processing measured the subjects' gait length, gait width, gait amplitude, gait speed, gait frequency, and symmetrical indicators, and the motion angles of the hip, knee, and ankle in the gait cycle were measured and recorded in real-time using a three-dimensional spiral measuring instrument fixed on the subject's hip, knee, and ankle.

Statistical analysis

SPSS statistics software (version 23.0, IBM, Armonk, NY, USA) was used for data analysis. Nonnormally distributed continuous data are described as medians and quartiles. The Spearman correlation coefficient was used to analyze the correlation between the modified MAS and surface electromyography parameters. A Wilcoxon signed ranks test was used to analyze the differences in MAS, CSS, gait parameters, FAC, SCIM, and mSCI-SET before and after treatment. The statistical test level was set to $P < 0.05$.

Results

Participants

Seventeen patients met the inclusion criteria and underwent surgical intervention. However, 3 patients who were unable to undergo follow-up due to the COVID-19 epidemic situation were excluded from the trial, and the remaining 14 patients completed preoperative and postoperative spasticity evaluations. Eight patients completed gait analysis. All of the patients underwent cSPNs, and a total of 26 obturator nerve SPNs, 26 tibia nerve SPNs, and 4 Hamming branches of sciatic nerve SPNs were performed. None of the patients postsurgery had any significant surgical complications, and no new skin paraesthesia or neuralgia was found (Table 1).

Spasticity assessment

After the operation, the patients' lower limb spasticity level improved immediately. The hip adductor, triceps surae, and hamstring muscle MAS scores were significantly lower than those before the operation ($P < 0.01$). The score of the comprehensive spasm scale (CSS) before surgery revealed moderate spasticity in 10.7% of patients and severe spasticity in 89.3% of patients. The postoperative CSS score was significantly reduced compared with the preoperative CSS score ($P < 0.01$). Moderate spasm was noted in 14.3% of patients, mild spasm was noted in 17.9%, and no spasm was noted in 67.8%. A significant correlation was noted between the MAS scores of the hip adductors and triceps surae and hamstrings and the RMS values (RMS(max)) of the sEMG

Table 1 Basic information and operation methods of 14 participants

Cases	Age	Sex	Etiology	Level of injury	ASIA	Operation method
1	34	M	Trauma	T10	D	Bilateral ON-SPN + bilateral TN-SPN
2	29	M	Trauma	C4	D	Bilateral ON-SPN + bilateral TN-SPN
3	31	M	Infection	T12	D	Bilateral ON-SPN + bilateral TN-SPN
4	65	M	Trauma	C4	D	Bilateral ON-SPN + bilateral TN-SPN
5	24	M	Tumor	T4	D	Bilateral ON-SPN + bilateral TN-SPN
6	62	M	Trauma	L1	D	Bilateral ON-SPN + bilateral TN-SPN
7	49	M	Trauma	C4	D	Bilateral ON-SPN + bilateral TN-SPN
8	54	M	Trauma	C5	D	Bilateral ON-SPN + bilateral TN-SPN
9	36	F	Tumor	T9	C	Bilateral ON-SPN + bilateral TN-SPN
10	39	M	Trauma	L2	C	Bilateral ON-SPN + bilateral TN-SPN + bilateral HB-SPN
11	46	M	Trauma	T4	B	Bilateral ON-SPN + bilateral TN-SPN
12	26	M	Trauma	T6	A	Bilateral ON-SPN + bilateral TN-SPN
13	40	M	Trauma	T7	A	Bilateral ON-SPN + left TN-SPN + right HB-SPN
14	64	F	Trauma	T10	D	Left TN-SPN + left HB-SPN

ASIA, American Spinal Injury Association impairment scale; *ON-SPN*, obturator nerve SPN; *TN-SPN*, tibial nerve SPN; *HB-SPN*, hamstring branch SPN

Table 2 Overtime change in spasticity, sEMG, and activities of daily living of 14 patients

	Preoperation	Postoperation	*P*-value
MAS (0–5)			
MAS total	4.00(4.00–4.00)	1.00(1.00–2.00)	<0.01
Hip adductor muscle	4.00(4.00–4.00)	1.00(1.00–2.00)	<0.01
Triceps surae muscle	4.00(4.00–5.00)	1.00(1.00–1.00)	<0.01
Hamstrings	4.00(4.00–4.00)	0.25(1.00–1.00)	0.059
CCS	16.00(15.00–16.00)	7.00(6.00–8.75)	<0.01
sEMG RMS (uV)			
RMS total			
Mean value	24.15(11.32–50.47)	10.12(5.56–18.85)	<0.01
Max value	37.20(21.85–76.15)	20.05(9.95–32.20)	<0.01
RMS hip adductor muscle			
Mean value	27.85(15.97–60.07)	16.30(9.83–24.82)	<0.01
Max value	57.80(28.05–106.25)	28.65(19.22–38.62)	<0.01
RMS triceps surae muscle			
Mean value	16.00(6.17–49.17)	11.44(4.05–17.30)	0.068
Max value	46.00(22.32–115.5)	12.85(6.58–21.12)	<0.01
RMS hamstrings			
Mean value	26.35(17.57–43.15)	11.44(4.05–17.30)	0.068
Max value	51.65(31.12–81.95)	20.70(5.75–34.82)	0.144
FAC	0.00(0.00–2.25)	2.00(1.75–4.00)	<0.01
SCIM	55.50(51.00–71.50)	69.00(51.00–77.75)	<0.01
SCI-SET	−37 ((−52)–(−27.5))	−5 ((−21)−2)	<0.01

MAS: grade 0 = 0, grade 1 = 1, grade 1 + = 2, grade 2 = 3, grade 3 = 4, grade 4 = 5;

CSS: 0–6 points no spasticity; 7–9 points mild spasticity; 10–12 points moderate spasticity; 13–16 points severe spasticity;

MAS and RMS total: data include hip adductor, triceps surae, and hamstrings

time-domain analysis parameters ($P < 0.01$), and the RMS values of the hip adductors and triceps surae were significantly reduced compared with the preoperative period in the patients (Table 2).

Evaluation of the ability to exercise and perform daily life activities

Postoperative patients' FAC grade was improved compared with that before operation ($P < 0.01$). SCIM was significantly improved compared with that noted preoperatively ($P < 0.01$), and the SET score was significantly improved compared to that obtained before the operation ($P < 0.01$) (Table 2).

The results of gait analysis showed that the degree of postoperative varus foot was significantly improved compared with that before surgery ($P < 0.01$), and the maximum knee flexion angle in the standing stage was reduced ($P < 0.05$). No significant differences in gait length, range, width, or pace were noted compared with preoperative values ($P > 0.05$) (Table 3).

Discussion

In this study, patients with spasticity of MAS 3–4 grade of lower limbs after spinal cord injury were rated with moderate to severe spasticity based on CSS, and most patients were ASIA D grade. For patients with ASIA D grade, the purpose of surgery is to relieve spasms and improve lower limb weight-bearing and walking function. However, in patients with A–C grades, the purpose of surgery is to relieve spasms of the lower limbs, improve spastic pain, create better rehabilitation training conditions for patients, and reduce caregiver workload. To minimize the recurrence of spasticity after surgery, we selected patients with stable spasticity for surgery (no change in the degree of spasticity in the last 6 months).

First, neurotomies in the lower limbs have been pioneered by orthopedic surgeons and were introduced in neurosurgery in the seventies by Gros and coworkers [11]. Then, the neurotomies were refined and made selective using microsurgical dissection and intraoperative electrostimulation for mapping the fascicles and quantifying the amount of fibers cut by Sindou and coworkers from Lyon University [23]. Later, the team had several consecutive publications detailing the surgical steps and precautions for SPN of the lower extremities, clarifying that cutting 50–80% of all branches to a targeted muscle could achieve the treatment of spasticity and emphasizing the importance of preoperative multidisciplinary evaluation and postoperative rehabilitation [7, 24, 25]. SPN aims at re-equilibrating the tonic balance between agonist and antagonist muscles by reducing excess spasticity. This procedure is gradually being used to treat focal spasticity of the limbs after cerebral palsy, stroke, or spinal cord injury.

Which peripheral nerve branches need to be combined and resected and in what proportion is individualized, taking into account the functional needs of the patient in addition to the need to balance the muscle tone and strength of agonist and antagonist muscles and to minimize the muscle tone while preserving enough muscle strength. Similar to data from Sindou et al. as mentioned above, we cut at least 50% of the nerve branches and electrically stimulated the nerve dissection proximally and distally intraoperatively to observe the relief of spasticity. In addition, we usually partially resect the posterior branch of the obturator nerve to better relieve hip internal retractor spasms. We would like to stress the fact that knee flexion is also dependent on the gastrocnemius muscles at the upper part of the popliteal region. In patients with spastic foot combined with spastic hamstrings, we always perform tibial neurotomy first. Then, the degree of relief of knee flexion spasm is observed, and hamstring neurotomy is performed if the result is unsatisfactory.

The assessment of the efficacy of the procedure in this study was comprehensive. Both clinical assessments and neurophysiological measurements (MAS, CSS, sEMG) for the spasticity itself as well as assessments of overall function and activities of daily living (gait analysis, FAC, SCIM, and mSCI-SET) were performed.

This study combined the clinical assessment of spasticity with neurophysiological measurements of muscle activity levels to more accurately assess the therapeutic

Table 3 Changes over time in gait kinematics of 8 patients

Gait parameters	Preoperation	Postoperation	P-value
Stance phase (%)	83.40(74.42–89.65)	82.35(76.52–86.10)	0.38
Swing phase (%)	16.60(10.35–25.57)	17.65(13.90–23.47)	0.38
Step speed (km/h)	0.75(0.32–1.65)	0.85(0.63–1.20)	0.932
Step length (cm)	25.00(15.50–35.00)	27.00(21.50–30.75)	0.717
Stride (cm)	53. 50(29.00–76.00)	54.00(41.50–60.50)	0.889
Step width (cm)	9.00(5.00–16.75)	12.50(11.25–17.25)	0.233
Max hip flexion angle (°)			
Swing phase	21.70(14.17–30.17)	19.65(15.57–24.25)	0.438
Stance phase	18.9(12.87–26.40)	17.40(12.42–22.95)	0.205
Max knee flexion angle (°)			
Swing phase	32.50(28.05–41.75)	27.60(20.75–35.77)	0.326
Stance phase	34.70(23.8–41.05)	25.50(16.125–33.12)	0.017
Max angle of foot varus (°)			
Swing phase	13.85(8.61–18.70)	8.36(6.76–11.47)	0.030
Stance phase	12.75(7.92–17.27)	7.67(7.00–10.12)	0.009

effects of cSPN. The results showed that surgery could significantly reduce the degree of spasm of the lower limbs in patients with spinal cord injury. The patients' MAS was reduced from a preoperative evaluation score of 3–4 to a postoperative evaluation score of 0–1. In addition, the CSS evaluation of spasm degree was reduced from severe spasm preoperatively to mild spasm or no spasm postoperatively. The MAS is currently the main method of clinical assessment of spasticity. However, MAS is based on a semi-quantitative method of empirical assessment, so it is not sensitive enough to detect slight changes in the patient's condition [5]. Previous studies have shown that compared with MAS, CSS is more reflective of the degree of spasm of the lower limbs [18].

We used sEMG to collect adductor, gastrocnemius, and hamstring muscle electrical signals during passive joint movement on the same day as the clinical evaluation. The study first confirmed that RMS was positively correlated with MAS of the lower limbs, i.e., the heavier the degree of spasm, the greater the RMS value. Moreover, the patients' RMS values of the adductor muscle, triceps surae, and hamstring sEMG parameters after cSPN surgery were significantly lower than those before the operation. The RMS value of sEMG is more sensitive to changes in spasm than the clinical spasm scale, so the RMS value is considered an effective parameter for predicting the effect of spasticity treatment [4, 27].

Gait analysis showed that 8 patients graded ASIA D had limited motion range of the hip, knee, and ankle; excessive knee flexion in the standing position; varus foot; foot ptosis; and scissor gait before surgery. After surgery, with the decrease in muscle tone, the adduction and internal rotation of the hip joint were corrected, and the step width increased. In addition, the standing knee joint flexion deformity, varus foot, and scissor gait were significantly improved. The patient's walking stability was strengthened, and balance function was improved. There were no significant differences in the basic parameters of gait (step length, stride speed, step width, stride range) and the angle of hip flexion and knee flexion in the swing phase compared with preoperative surgery. This finding may be related to the fact that the patient did not undergo sufficient time-standardized rehabilitation training and the follow-up evaluation time after the surgery was short [13, 21]. FAC results show that the patient's gait after surgery was better than that before surgery, and some patients could walk independently after surgery. Therefore, cSPN can improve the walking ability of patients with lower limb spasms after SCI and create favorable conditions for subsequent rehabilitation training, such as gait training and balance ability training.

Patients' ability to perform activities of daily living after spinal cord injury is generally reduced. This finding is not only related to the patient's age, degree of injury, level of injury, social support, and economic situation but also affected by the degree of neuralgia and spasms [3]. The results of this study showed that the patients' postoperative SCIM scores were significantly higher than those before surgery mainly due to the improvement of indoor and outdoor walking ability scores, which was related to decreased muscle tone, abnormal gait correction, postural improvement, and stable walking ability improvement after surgery. These patients also generally improved in areas such as postoperative daily care and wheelchair access. Postoperative SCI-SET evaluation showed a reduction in the negative effects of spasms of the lower limbs, and patients all showed a more positive outlook on life after surgery.

This study has the following limitations: (1) Only 3 patients underwent sciatic nerve SPN based on 4 hamstring branches. No significant differences in the MAS classification and sEMG parameters of the hamstring muscle were noted before and after surgery. Thus, the surgical efficacy of sciatic nerve SPN needs to be further explored and verified. (2) The lack of follow-up for more than 1 year is mainly because most of the surgical patients are from other various cities, and it was difficult to return to the hospital multiple times for follow-up. In addition, the length of follow-up was also affected due to widespread of COVID-19 in recent years.

Conclusions

Combined selective peripheral neurotomy can effectively reduce spasticity of the affected limb, improve the weight-bearing walking function of the lower limb, improve the patient's ability to live independently, and create favorable conditions for nursing and rehabilitation.

Declarations

Ethics approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the medical ethics committee of China Rehabilitation Research Center (ethics No. 2016–055-1) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Conflict of interest The authors declare no competing interests.

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