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GENERAL ORTHOPAEDICS

Current techniques for the treatment of spasticity and their effectiveness

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- This review highlights the role of existing spasticity treatment methods in reducing muscle tone and improving function. The surgical methods today mainly include selective dorsal rhizotomy, selective neurotomy, intrathecal baclofen treatment (ITB), etc. These techniques (except ITB) can lower patients' muscular tone in the long term and improve function to some extent. The young procedures, contralateral C7 nerve transfer and T1 neurotomy, are still under research.
- ITB and nonsurgical treatment methods, botulinum toxin A (BoNT-A) and extracorporeal shockwave therapy (ESWT), can reduce muscle tone in the short term, but the long-term efficacy is unsatisfactory. In addition, the effects of improving function are relatively controversial. The economic cost of these treatment methods is also heavy for patients.
- In addition, some studies have reported that some kinds of electrical/magnetic stimulation can improve the patients' function. They can potentially be used as an adjunctive treatment for spasticity.
- According to current studies and our own experience, surgery methods (except ITB) are still recommended for patients, whose spasticity has a major detrimental influence on their everyday lives, taking into account patient benefits and cost-effectiveness.
- There are also some problems in the current research on spasticity treatment, such as incomplete guidelines and a relative lack of high-quality studies, which is what the doctors need to strive for. Further exploration is needed to find the treatment methods that can reduce muscle tone while improving patients' function to better benefit patients.

Keywords: spasticity; selective dorsal rhizotomy (SDR); selective neurotomy; contralateral C7 nerve transfer; intrathecal baclofen (ITB); botulinum toxin A (BoNT-A); extracorporeal shock wave therapy (ESWT)

Introduction

Spasticity is a kind of motor disorder, characterized by a velocity-dependent increase in the tonic muscle tension reflex (muscle tone) (1). It could progressively induce muscle atrophy, fibrosis and contracture, bringing negative impacts on the patient's everyday life (2). There are a variety of central nervous system disorders that can lead to spasticity, including multiple sclerosis, cerebral palsy (CP), stroke, spinal cord injury, brain trauma, etc. (3, 4). Stroke is a significant contributor to adult spasticity; around 50% of stroke survivors will experience the problem of spasticity, which can significantly impair their ability to do daily activities (5). For children, between two and three out of every 1,000 live newborns, around 80% of which have spasticity, are born with CP, the most prevalent physical disability in children (6).

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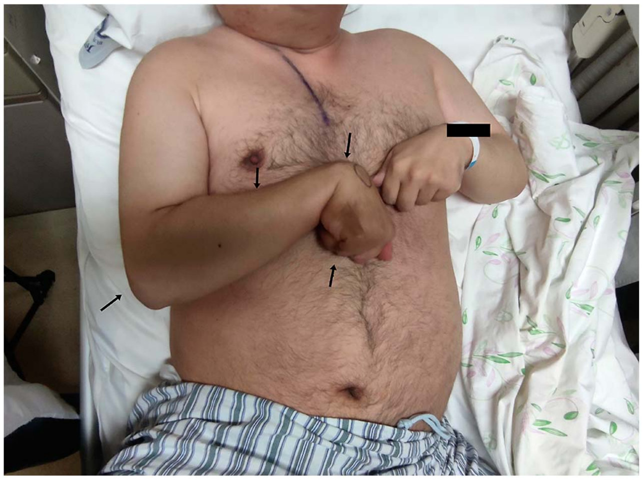

Figure 1

Upper limb spasticity forearm pronation, elbow, wrist and finger flexion.

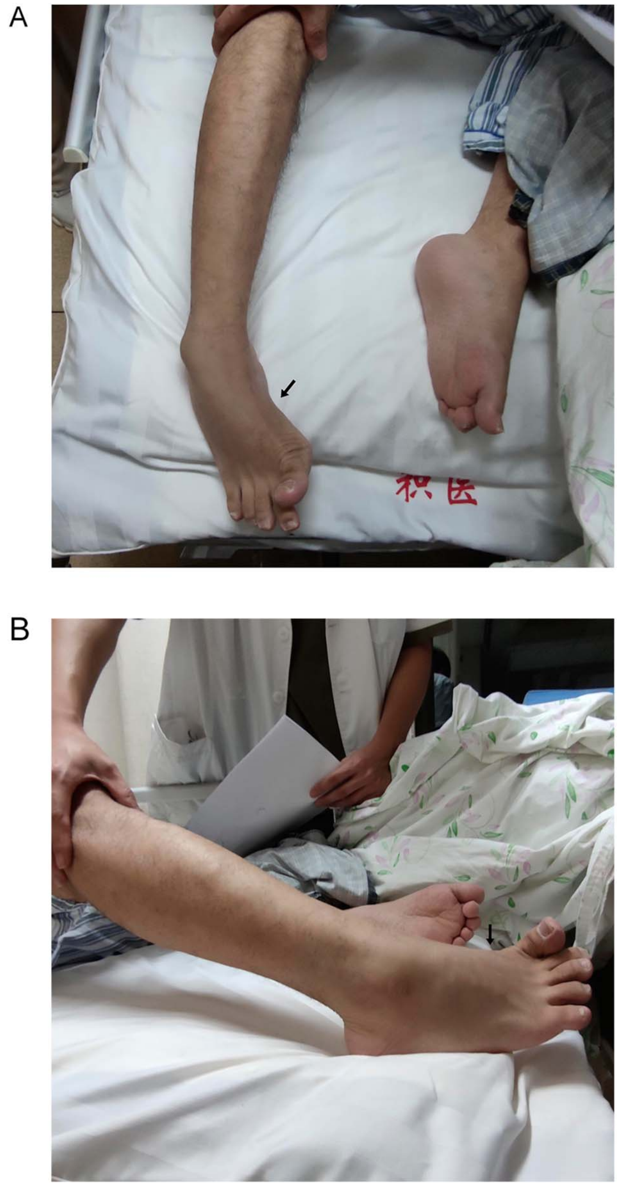

Figure 2

(A) Positive view of spastic equinovarus foot. (B) Lateral view of spastic equinovarus foot.

There are a variety of clinical features about spasticity which can lead to deformity of the limbs. Upper limb spasticity may present as pronation and adduction, accompanied by forearm pronation, elbow, wrist and finger flexion (5) (Fig. 1). Lower limb spasticity may present as spastic equinovarus foot (Fig. 2) and be associated with poor posture and gait efficiency, misaligned bones, reduced self-care capacity, increased pain and decreased total functional activity (7).

In actuality, the loss of normal life and function caused by spasticity imposes a great burden on both the patients and their families. How to effectively treat spasticity is currently a research focus.Doctors hope to find a cost-effective treatment method that can simultaneously reduce muscle tone and improve the function in the long term. At present, the treatment methods for spasticity include surgical and nonsurgical treatments. Surgical treatment methods mainly include selective dorsal rhizotomy (SDR), selective neurotomy, intrathecal baclofen treatment (ITB) and the under researching surgical techniques including contralateral C7 nerve transfer and T1 neurotomy. Nonsurgical treatment methods include electrical/magnetic stimulation, shockwave, botulinum toxin injection, etc. (1, 6). Although none of them are perfect, each treatment method has its own characteristics. We hope to provide a review of the commonly used and relatively effective methods for treating spasticity to provide reference for scholars and doctors in related fields and promote further exploration of spasticity treatment.

Methods

PubMed was used as the main database to search for information along with Embase and CNKI. The electronic search strategy, taking PubMed as an example, included searching keywords such as ‘spasticity’, ‘rhizotomy’, ‘C7 transfer’, ‘neurotomy’, ‘baclofen’, ‘electrical stimulation’, ‘botulinum toxin A’, ‘shock wave’, etc. Then we analyzed the results, excluded irrelevant literature and finally conducted a review of relevant literature. Most studies have been published in the past 10 years.

Selective Dorsal Rhozotomy

Selective Dorsal Rhozotomy (SDR) is a common and irreversible surgical technique used for spasticity

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Table 1 Summary of SDR related research.

Study	Etiologies	Patients, *n*	Age (mean ± SD)	Spastic limbs	Follow-up period	Efficiency of SDR	
						Muscle tone	Function
MacWilliams *et al.* (13)	CP	SDR: 35; CON: 40	SDR: 5.4 ± 1.4; CON: 7.3 ± 0.8	Lower limbs	BL, over 10 years	+	Long term: –
Marron *et al.* (14)	CP	SDR: 22; CON: 17	SDR: 11.7 ± 2.9; CON: 1.8 ± 1.2	Lower limbs	BL, 1 year, 5 years	NA	1 year: +; 5 years: – (similar to CON)
Jiang *et al.* (11)	CP (GMFCS I, II, III)	32	5.9 ± 2.1	Lower limbs	BL, 379 ± 187 days	+	+
Gillespie *et al.* (12)	CP (GMFCS IV, V)	144	8.3 ± 0.3	Lower limbs	BL, 2 years	+	Most patients: +
Oraee-Yazdani *et al.* (2)	SCI	10	30.8 ± 5.7	Lower limbs	BL, 1 week, 3 months, 6 months, 1 year	+	+
Pu *et al.* (10)	Meningioma; stroke; TBI; HSP	8	32.88 ± 7.75	Lower limbs	BL, 1 year	+	+

GMFCS, gross motor function classification system; BL, baseline; CON, control group; CP, cerebral palsy; SCI, spinal cord injury; TBI, traumatic brain injury; HSP, hereditary spastic paraplegia; NA, not available; '+' the improvement of spasm or function; '–' no improvement of spasm or function.

treatment, commonly used in children with spastic CP to improve lower limb spasticity (8). As research continues, SDR has also been reported for adults. The surgical approach is to expose nerve roots at the lumbosacral level through laminoplasty or single segment laminectomy, and then use the electrophysiological response of intraoperative electrical stimulation to determine and selectively cut off the nerves that lead to muscle tension increase, while preserving the patient's normal function, such as walking, sphincter function and sensory (9, 10). The number of nerves to be cut off during SDR needs to be carefully determined according to the patients' actual situation. Removing too many nerve fibers may lead to weak muscle strength, dysfunction bladder and intestinal, and in the long run, may also cause spinal abnormalities (such as scoliosis, kyphosis and lumbar hyperlordosis). Removing too few nerves, however, may cause incomplete spasticity release, which may further lead to hip dislocation (9). Surgeons may need to utilize X-rays to count vertebrae during SDR, especially single-segment SDR, but X-rays might expose patients and surgeons to more radiation, and taking X-rays may briefly interrupt the surgical process. Some researchers are currently investigating alternative methods of X-ray. For instance, Gelder *et al.* (8) suggest that the combination of early percutaneous ultrasound and intraoperative ultrasound can accurately identify the level of the conus medullaris and improve surgical efficiency, which may be a better way.

Many prior studies have reported the efficiency of SDR (Table 1). Jiang *et al.* (11) conducted a short-term follow-up (within 2 years) study involving 32 children with CP. They found that SDR can significantly reduce the patient's scores of modify Ashworth scores (MAS), indicating a significant improvement in spasticity. In a study of 114 children, Gillespie *et al.* (12) found that the mean MASs reduced significantly and most patients' gross motor function improved in 2 years after SDR surgery. MacWilliams *et al.* (13) followed patients for more than 10 years and they also found that SDR could dramatically alleviate spasticity, but had minimal long-term effects on patients' motor function and quality of life. Marron *et al.* (14) discovered that, whereas the gait of SDR patients improved significantly in the short term (within 1 year) after SDR, the patients in SDR group and non-SDR group had similar kinematic results during a 5-year follow-up. Similarly, McMulkin *et al.* (15) conducted a follow-up study over 10 years. They compared the kinematic parameters of spasticity patients who underwent SDR with those who did not. The results showed that SDR could not improve patients' gait. Grunt *et al.* (16) concluded a meta-analysis to analyze the long-term effect of SDR and found that SDR has a moderately positive long-term influence on the body structure and body function domains of International Classification of Functioning, Disability and Health (ICF), but lack the evidences on the ICF activity and participation domains. Therefore, we can believe that SDR has a considerable effect in reducing spasticity in children, but plays a controversial role in the improvement of patients' function. Some studies have shown that adherence to postoperative rehabilitation treatment and active exercise may promote functional recovery, but the problem is the lack of norms and guidelines for postoperative physical therapy of SDR. (7, 11, 17).

Previous studies have also shown that preoperative and postoperative gross motor function classification system (GMFCS) ratings are of great significance in guiding the treatment and prognosis evaluation for CP patients. The patients with GMFCS grades II/III can benefit more from SDR and have better prognosis, while the patients with GMFCS grades IV/V benefit less from SDR (12, 18, 19). Therefore, we suggest that, for children with spastic CP, sufficient preoperative and postoperative GMFCS ratings should be conducted to better guide treatment.

There are also studies reporting that SDR was used in spastic adult patients. Oraee-Yazdani *et al.* (2) studied the effectiveness of SDR in ten adult patients with spasticity caused by spinal cord injury (six patients with cervical cord

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injury and four patients with thoracic cord injury). The follow-up period was 1 year, and the results showed that there were no surgical-related complications or adverse events in the patients during the 1-year period. Moreover, the MAS significantly decreased, and the quality of life and functional score also significantly improved. Therefore, SDR can be considered an effective treatment for adult spasticity. Pu *et al.* (10) reported the successful use of modified SDR (single laminectomy with exposed nerve roots) in the treatment of eight adult patients with lower limb spasticity. Postoperatively, the patients' Ashworth score, Gross Motor Function Measure-66 (GMFM-66) score and knee, ankle and hip joint mobility were significantly improved without complications. Therefore, SDR seems an effective method on treating adult spasticity. Unfortunately, due to the lack of studies, we still need to further explore the effectiveness of SDR in treating adult spasticity.

In conclusion, SDR is an effective treatment for relieving spasticity in children, mainly used for lower limb spasticity, and its effect on functional improvement is relatively controversial. SDR can also be used in treating adult spasticity.

Selective neurotomy

Selective neurotomy is an effective and long-term surgical approach that can improve focal spasticity in patients (20). It is considered as an alternative treatment for botulinum toxin A and baclofen in treating spasticity (21). The surgery is roughly as follows: under general anesthesia, the target nerve that innervates a certain muscle is separated and then the sensory and motor branches are determined through intraoperative electrical stimulation. The sensory branch is preserved and the motor branch is partially cut, with a cutting ratio between 50 and 80% (22). At present, selective neurotomy mainly includes selective neurotomy of tibial nerve for equinovarus foot, selective neurotomy of musculocutaneous nerve for elbow flexor spasm, selective neurotomy of median nerve and ulnar nerve for spastic hand, selective neurotomy of femoral nerve for knee stiffness, etc. (20).

The effects of selective neurotomy have been reported many times in the prior studies (Table 2). Liu *et al.* (23) explored the efficacy of combined selective peripheral neurotomy in the treatment of limb spasticity after spinal cord injury, selectively cutting obturator nerve (26 branches), tibial nerve (26 branches) and sciatic nerve (four branches) to observe the efficacy of easing spasm of hip adductor muscle, calf triceps muscle and hamstring muscle. The results showed that MASs of hip adductor muscle and calf triceps were significantly reduced after surgery, but there was no significant difference in MASs of hamstring muscle before and after surgery, and patients' gait, motor function and activities of daily living were significantly improved after surgery. Gross *et al.* (21) investigated the effect of selective neurotomy of the rectus femoris nerve on spastic stiff knee gait. Seven spastic patients underwent surgery, and a reduction in spasticity and improvement in maximum walking distance, step speed, stride length and other kinematic parameters were observed 3 months after surgery. Therefore, they believe that rectus femoris nerve transection improves the stiff gait of the knee joint in patients. To explore the long-term efficacy of selective neurotomy, Dauleac *et al.* (24) conducted a study involving 88 patients with spastic feet and evaluated the efficacy at 1 year (T1) and 5 years (T5) after selective neurotomy. The goal attainment scaling methodology (T-score), the proportion of deformities, MAS and modified Rankin Scale (mRS) are evaluated,

Table 2 Summary of studies of selective neurotomy.

Studies	Etiologies	Patients, *n*	Age	Targeted nerves	Follow-up period	Efficiency of SN: Muscle tone	Efficiency of SN: Function
Liu *et al.* (23)	SCI	14	43 ± 14	Obturator nerve, tibial nerve, sciatic nerve	BL, 1 year	+	+
Gross *et al.* (21)	SCI; stroke	7	47 ± 6	Femoral nerve femoral rectus branch	BL, 3 months	+	+
Dauleac *et al.* (24)	Stroke; TBI; MS; SCI	88	39.6 ± 16.7	Tibial nerve	BL; 1 year; 5 years	+	+
Leclercq *et al.* (25)	Stroke; CP; TBI; SCI	42	Adult: 47.2; children: 14.4	Musculocutaneous nerve, ulnar nerve, median nerve	BL; 6 months; 31 months	+	–
Maarrawi *et al.* (26)	Stroke, trauma, CP	31	38 ± 16	Musculocutaneous nerve, ulnar nerve, median nerve	BL; 1–10.2 years (mean 4.5 years)	+	+*
Sitthinamsuwan *et al.* (27)	Stroke; TBI; SCI; CP; encephalitis; HBI; MS	33	47 ± 21	Lateral thoracic nerve, musculocutaneous nerve, ulnar nerve, median nerve, obturator nerve, tibial nerve	BL; 4–28 months (mean: 21.1)	+	+

SCI, spinal cord injury; BL, baseline; SN, selective neurotomy; TBI, traumatic brain injury; MS, multiple sclerosis; CP, cerebral palsy; HBI, hypoxic brain injury; '+' the improvement of spasm or function; '–' no improvement of spasm or function.
*In most patients.

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and the results showed that 88.7% of patients achieved at least the 'expected' goal at T5, and the MASs, the proportion of deformities and mRS scores at T1 and T5 were significantly better than those before procedure. Leclercq *et al.* (25) investigated the efficacy of hyperselective neurectomy in the treatment of upper limb spasticity. They included 42 spastic patients and selectively cut off the musculocutaneous nerve, ulnar nerve and median nerve, and observed their effects on the flexor elbow muscle, flexor wrist muscle, etc. The average follow-up period was 31 months. During the follow-up, it was found that although two patients had recurrent elbow spasticity, the overall improvement of spasticity was sustained and muscle strength did not decrease. However, in a study by Sindou *et al*, the recurring rate was about 15.6%, which is higher than Leclercq *et al.*'s study (25, 26). Maarrawi *et al.* (26) conducted a follow-up study on 31 patients with central limb spasticity, with an average follow-up time of 4.5 years, to evaluate the therapeutic effect of selective neurotomy of musculocutaneous nerve, ulnar nerve and median nerve on upper limb spasticity. The results showed that patients generally experienced relief from spasticity, and their daily living abilities also improved significantly. Sitthinamsuwan *et al.* (27) simultaneously evaluated the efficacy of selective peripheral neurotomy in treating upper and lower limb spasticity, with significant improvements in postoperative MAS and PROM scores. The postoperative patient's MAS and PROM score significantly improved. Among the 18 patients with no upper limb function, three showed improvement in hand function after surgery, 10 out of 11 patients with selective neurotomy of tibial nerve showed improvement in gait and nine patients with selective neurotomy of sciatic nerve, all showed improvement in sitting function or gait after surgery. Therefore, it can be considered that selective nerve resection can effectively alleviate patient spasms and improve function.

Sadly, there are relatively limited number of high-quality studies on selective neurotomy for the treatment of limb spasticity, especially the reports on selective neurotomy for the treatment of spasticity in the lower limbs. Most studies are limited to case reports or small sample, short-term follow-up studies. According to existing studies, selective neurotomy may be a good surgical method for treating spasticity, and it may improve patient function while improving spasticity. However, based on the current lack of high-quality and large sample clinical studies, future scholars need to further explore the specific application effects of selective neurotomy to provide sufficient research support.

Contralateral C7 nerve transfer

It should be noted that contralateral C7 nerve transfer is a young technique and is still under research in some select few centers, so it should not be considered as a procedure at a similar weight as SDR and selective neurotomy and it is not a robust option as yet. It is mainly used for the treatment of upper limb spasticity in patients with chronic brain injury. The general process of C7 transfer is to cut off the C7 nerve on the healthy side (non-paralyzed side) from a distance while cutting off the C7 nerve on the affected side from the proximity. Then, the C7 nerve root on the healthy side is moved to the affected side to connect with the C7 nerve on the affected side, thereby improving the upper limb spasticity (28, 29). Its feasibility is that the C5-T1 nerve roots form the brachial plexus, of which the C7 nerve accounts for about 20% of its nerve fibers, and the function often overlaps with other nerves. Moreover, the sensory or motor impairments caused by C7 section on the healthy side of the limb may be gradually restored, making the C7 nerve an ideal donor (30). C7 nerve transfer is mainly used in the treatment of brachial plexus injury and the use in the treatment of limb spasticity began in recent years (29). We only discuss its characteristics for the treatment of spasticity.

C7 nerve transfer can be achieved through different pathways (31). In Hua *et al.*'s study, a cervical subcutaneous pathway was used, which requires 3–4 patients' gastrocnemius nerves to bridge the healthy C7 nerve and the affected C7 nerve. However, this causes more damage to the patients and the effects may also be compromised (32). The anterior vertebral approach at Huashan Hospital is now considered the first choice of treatment for spasticity (31). However, the surgical risk and difficulty are relatively high on this route because it is adjacent to the vertebral vessels, recurrent laryngeal nerve, phrenic nerve, thoracic duct, esophagus, etc. In addition, the movement of the esophagus may hinder nerve growth, and some patients still have the problem of insufficient C7 nerve length, so exploring new routes is still needed (31). Guan *et al.* (33) reported a way of C7 nerve transfer via cervical posterior approach, and most patients showed significant improvement in spasticity after surgery. However, due to the short follow-up time and small number of patients, further exploration is needed to determine the effectiveness of this pathway.

Studies in recent years have reported the efficiency of contralateral C7 nerve transfer in the treatment of spasticity (Table 3). To investigate the effectiveness of C7 nerve transfer in treating limb spasticity, Zheng *et al.* (28) conducted a randomized-controlled trial (RCT) involving 36 patients (18 patients underwent C7 transfer surgery and 18 patients only received physical therapy). After a 1-year follow-up, they found that patients who underwent C7 transfer had significantly improved spasticity and motor function, thus demonstrating the effectiveness of C7 nerve transfer in treating spasticity. Hua *et al.* (32) also reached similar conclusions in a 2-year follow-up study. They found that C7 nerve displacement can effectively alleviate spasms and improve function in patients, establishing a physiological connection between the ipsilateral cerebral hemisphere and the paralyzed

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Table 3 Summary of C7 transfer related studies.

Study	Etiology	Patients, *n*	Age (mean ± SD)	Spastic limbs	Follow-up period	Efficiency of C7 transfer	
						Muscle tone	Function
Zheng *et al.* (28)	Stroke; TBI; CP; encephalitis	OP: 18; CON: 18	OP: 27 ± 9; CON: 26 ± 8	Upper limbs	BL, 1 year	+	+
Hua *et al.* (32)	Cerebral hemorrhage; TBI; CP	OP: 6; CON: 6	OP: 26 ± 3; CON: 26 ± 4	Upper limbs	BL; 6; 12; 18; 24 months	+	+
Feng *et al.* (34)	Stroke; CP; TBI; encephalitis	OP: 168; CON: 168	OP: 36 ± 15; CON: 40 ± 15	Upper limbs	BL; 2 years	+	+

TBI, traumatic brain injury; OP, operation group; BL, baseline; CON, control group; CP, cerebral palsy; '+' the improvement of spasm or function; '–' no improvement of spasm or function.

hand. To investigate the effectiveness of C7 nerve transfer in a broader population, Feng *et al.* (34) conducted a multicenter retrospective study involving up to 336 patients of different ages (4–69 years), genders, onset times and etiologies. After a 2-year follow-up, they found that patients with C7 transfer had more significant improvements in spasticity and function. It is worth noting that they conducted subgroup analysis. The study has shown that FMA-UP scores significantly increased in various subgroups of age, disease duration, degree of paralysis and cause of injury, with no occurrence of serious complications or other adverse consequences. Therefore, they believe that C7 transfer is a safe and effective method to treat upper limb spasticity, which can alleviate spasticity and improve function.

However, it should be noted that previous reports on C7 transfer cannot confirm whether the therapeutic effects come from the healthy C7 nerve or C7 transection due to insufficient follow-up period and lack of control group. And as far as we know, patients' long-term satisfaction with this surgery is still controversial, plus there is no perfect surgical path. Therefore, it remains to be discussed whether this treatment method should be given priority.

Intrathecal baclofen treatment

Baclofen is an agonist at the GABA-B receptor. It inhibits the release of excitatory neurotransmitters by interfering with voltage-gated calcium channels, thereby suppressing reflexive muscle contractions, and can be used to treat spasticity (35). Intrathecal baclofen treatment (ITB) is considered an effective treatment for improving spasticity (36). The procedure is as follows (35, 36, 37): the patient is positioned under general anesthesia in the lateral decubitus position with the operative side up. A subcostal abdominal incision is created between the iliac crest and the costal margin for the implantation of pump. In addition, a dorsal paramedian incision is made. The catheter is inserted through the paramedian incision and positioned into the intrathecal space of the target segments with fluoroscopic assistance. The catheter then travels from the back to the abdomen and is connected to the pump.

To evaluate the long-term effects of ITB on spasticity in patients with spasticity, Pucks-Faes *et al.* (38) conducted a retrospective study on seven patients with hereditary spastic paraparesis treated with ITB. They observed a significant decrease in spasticity and improvement in activity function in the first 2–3 years, which could remain stable for the following 4–5 years. However, the progression was slow and even deterioration of activity function occurred later, depending on the individual factors of the patients. Eventually, they believe that ITB can improve patient conditions in the first 6–8 years. To investigate the effectiveness of ITB in treating post-stroke spasticity, Creamer *et al.* (39) conducted a RCT, in which 60 post-stroke spasticity patients were randomly divided into two groups (experimental group of 31 patients and control group of 29 patients). The patients were followed up for 6 months to evaluate their spasticity, function and complications. The results showed that the improvement of spasticity in the ITB group was significantly better than that in the control group, and the improvement of motor function in the experimental group also tended to be better than that in the control group. The ITB group had more complications, but no serious complications occurred. Therefore, ITB can still be considered an effective treatment for post-stroke spasticity in adults. In another study, Creamer *et al.* (40) found that patients treated with ITB had relatively better quality of life and satisfaction compared to traditional treatment methods. To investigate the efficacy of ITB in treating spasticity in patients with primary lateral sclerosis, Zubair *et al.* (41) analyzed five patients with primary lateral sclerosis who received ITB for 4–15 years, with an average of 10.4 years. They found that all patients had a decrease in Ashworth score, indicating the effectiveness of spasticity improvement. Cozzi *et al.* (42) concluded through meta-analysis that ITB can alleviate spasticity in patients with multiple sclerosis-related spasms and have a positive impact on their quality of life and satisfaction. Dietz *et al.* (43) confirmed the effectiveness of ITB in improving spasticity in patients with spinal cord injury through meta-analysis. However, there has been a lack

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of high-quality and strong evidence in previous studies to further confirm the therapeutic effect of ITB, especially for children with CP. Therefore, more high-quality research is needed in the future (44).

In addition, several points need to be noted if we want to use ITB to treat spasticity: i) ITB may cause various complications, the most common of which are catheter-related complications, such as catheter twisting, occlusion, etc. Other complications include infection, loss of efficacy, etc. Bonouvrié *et al.* (36) reported that the related complications of silicone catheter were more than that of coated catheter, and we need to pay attention to perioperative anti-infection management, screening for common pathogenic bacteria, educating family members, etc. (36, 45); ii) patient factors such as underweight or overweight, trauma, infection, etc. may increase the risk of adverse events in ITB, making patient management particularly important (35); and iii) patients receiving ITB for spasticity require long-term medication. Sudden cessation of medication due to catheter displacement, battery failure, inability to obtain medication, etc. can lead to withdrawal syndrome such as increased muscle tone, hallucinations, severe temperature rise and multiple organ failure. Therefore, it is particularly important to establish a good prevention and treatment guidance (46).

In conclusion, ITB is an effective way to alleviate spasticity for 6–8 years, but there is still a lack of high-quality and strong evidence to further demonstrate its long-term effectiveness. In addition, choosing ITB treatment requires comprehensive consideration of the patient's actual situation, economic costs, prevention and management of complications.

Botulinum toxin A

Botulinum toxin A (BoNT-A) can block the release of acetylcholine at the neuromuscular junction, thereby alleviating spasticity (47). It has been widely used in clinical practice to treat spasticity.

To investigate the effects of BoNT-A injection into the rectus femoris muscle on gait and function in stroke patients, Tenniglo *et al.* (48) conducted a double-blind RCT involving 25 patients. They found that the experimental group improved the maximum flexion and range of motion of the knee joint by 6.7° and 4.8°, respectively, compared to the control group, and the 6 min walking test showed a significant increase of 18.3 meters. Therefore, BoNT-A is effective in improving knee joint movement. To investigate the long-term efficacy, Fheodoroff *et al.* (49) compared the long-term benefits of BoNT-A combined with rehabilitation therapy for 10 years with those of patients treated with rehabilitation therapy alone. The results showed that the combination of BoNT-A and rehabilitation therapy could reduce the risk of all-cause mortality by 8.8%, increase life years by 13% and increase life years by 59% after quality adjustment, with better cost-effectiveness. Kerzoncuf *et al.* (50) also investigated the effectiveness of BoNT-A treatment for post-stroke spasticity through RCTs. Forty patients were divided into an experimental group (19 patients treated with BoNT-A) and a placebo group (21 patients). In 4–6 weeks, the results showed that the spasticity condition in the experimental group improved better than that in the control group, and improvements in posture and activity could be observed. Similarly, to investigate the efficacy of BoNT-A in treating post-stroke lower limb spasticity, Doan *et al.* (47) conducted a meta-analysis of previous RCT studies. The results showed that after BoNT-A treatment, the tension of lower limb muscles significantly decreased in weeks 4 and 8, and was maintained until week 12. However, there are inconsistent views on the improvement of functional aspects such as walking ability, stride length, stride frequency and balance ability in patients. Andringa *et al.* (51) conducted a meta-analysis to investigate the effectiveness of BoNT-A in treating post-stroke upper limb spasticity. The results showed a general decrease in spasticity scores, but the authors concluded that BoNT-A cannot improve upper limb and hand function when used for upper limb spasticity. In terms of the efficacy of BoNT-A in treating spastic paraplegia patients, Diniz de Lima *et al.* (52) conducted a RCT. The experimental group received BoNT-A injection treatment for the adductor muscle and triceps calf, while the control group received placebo. The results showed that compared with the control group, the experimental group had a greater decrease in adductor muscle tone, but no significant improvement in gait, subjective sensation, muscle strength, etc. The incidence of complications was similar between the two groups. Therefore, it is believed that BoNT-A can improve spasticity and is relatively safe, but cannot improve function. Delgado *et al.* (53) evaluated the effectiveness of BoNT-A in treating upper limb spasticity in children, and observed improvement in spasticity after treatment. There is currently no clear conclusion to prove the effectiveness and safety of BoNT-A treatment in children with lower limb spasticity (54).

It should be noted that BoNT-A takes about 1–2 weeks to take effect. In addition, BoNT-A may cause various adverse reactions, including local effects (tenderness, swelling caused by local diffusion, etc.), systemic effects (including hypersensitivity reactions and potential autonomic nervous system dysfunction, such as dry mouth, no sweating, constipation, orthostatic hypotension, etc.) and reduced efficacy (repeated injections can stimulate the formation of antibodies in the body, reducing the therapeutic effect after injection) (55). Due to the limitations of injection techniques, dosage and patient factors, the effect of BoNT-A is often difficult to maintain in the long term and often fails to achieve ideal results (23). These problems need to be fully considered in clinical applications.

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In conclusion, BoNT-A has a relatively definite therapeutic effect on relieving limb spasticity in adults, but its role in improving function is controversial. There is relatively limited number of studies on the use of botulinum toxin for the treatment of spasticity in children, especially for lower limb spasticity. Therefore, further exploration is needed to explore its effectiveness.

Extracorporeal shockwave therapy

Extracorporeal shockwave therapy (ESWT) is a relatively new nonsurgical treatment method that has the advantages of noninvasiveness, safety, painlessness and simplicity. It decreases muscle tension by disrupting the connection between actin and myosin through vibration, thereby improving the spastic state of patients (56, 57).

There are currently two types of shockwave therapy, focused extracorporeal shockwave therapy (fESWT) and radial extracorporeal shockwave therapy (rESWT). The shockwave emitted by the former is concentrated in the target area, while the shockwave emitted by the latter can radiate energy through the skin in contact (57, 58, 59). However, Wu *et al.* (59) showed that although both can alleviate limb spasms, rESWT is more effective in relieving ankle passive range of motion and other aspects. And a meta-analysis has pointed out that rESWT is a better treatment option for spasticity compared to fESWT and BoNT-A therapy (57). Overall, rESWT seems to be a better option, but further high-quality studies are needed to confirm this.

To investigate the effectiveness of ESWT in treating spasticity, Vidal *et al.* (60) conducted a RCT involving 15 patients with CP. Patients were randomly divided into three groups: group A and group B received rESWT treatment, while group C received placebo. The results showed that the Ashworth scale scores and PROM were significantly improved in the rESWT treatment group, and the difference was statistically significant compared with the placebo group. Su *et al.* (61) also found that ESWT can alleviate spasticity, improve gross motor function of lower limbs and alleviate muscle stiffness in a study involving 15 children with CP and six children with advanced Rett syndrome. For patients after stroke, Wang *et al.* (62) conducted a RCT to investigate the efficiency of ESWT. 82 patients were enrolled and randomly divided into control group and the experimental groups. Patients were followed up for 4 weeks to evaluate patients' MASs, FMA scales and swelling degree. The results showed that the patients' MAS decreased, but there was no statistical difference in FMA and swelling degree. Therefore, they believe that shockwave can alleviate spasticity but have no effect on function. In a RCT involving 100 patients, Nada *et al.* (63) found that rESWT treatment can reduce foot spasms and spastic equinus deformity in stroke patients and increase mobility. In addition, Marinelli *et al.* (64) also confirmed the effectiveness of shockwaves in improving spasticity in patients with multiple sclerosis. Many previous meta-analyses have confirmed the effectiveness of shockwave therapy for limb spasticity. Kim *et al.* (65) found through meta-analysis that ESWT can improve spasticity, ROM scores and gait in patients with CP. It may enable CP patients to restore normal spastic gait patterns and maintain a healthy lifestyle. Mihai *et al.* (66) concluded through meta-analysis that shockwaves can effectively alleviate spasticity in post-stroke patients for 12 weeks, and can improve lower limb range of motion and pain.

Although studies have generally observed improvements in spasticity in patients with shockwaves, there is still some controversy over their role in restoring patients' function. For pediatric patients, Emara *et al.* (67) and El Shamy *et al.* (68) believe that ESWT can improve the function of children with CP. But Elnaggar *et al.* (69) hold the opposite view. The conclusion of Wang *et al.* and Daliri *et al.* (62, 70) regarding adult patients is that ESWT cannot improve their motor function. But Ou Yang *et al.* (55) believe that shockwave can relieve spasms in patients for 3 months, and functional improvement can be maintained for more than 2 weeks. However, Li *et al.* (71) found that the function of the hand and control of the wrist joint may recover to some extent with an increase in the number of shockwave treatments. Mihai *et al.* and Elnaggar *et al.* (69, 72) found in their studies that the combination of ESWT with other treatment methods such as orthotics, exercise and botulinum toxin may improve function. This may suggest that we can improve function by setting better ESWT frequency and parameters, or combining with other treatment methods.

In conclusion, ESWT can alleviate spasticity in patients and the effect can last for 3 months. Previous studies have also suggested that ESWT is more effective than electrical stimulation and BoNT-A (5, 73). However, there is still controversy over the improvement of patients' function. ESWT may improve patients' function by increasing the number of treatments or combining it with other treatment methods, but this still needs further confirmation.

Other techniques

The effective treatment methods for central limb spasticity are now a research hotspot in this field. In addition to the abovementioned treatment methods, there are still several potentially promising treatment methods.

Thoracic spinal nerve root 1 (T1) neurotomy

It is mainly used to treat hand flexion spasticity, which is still a great challenge nowadays. Yang *et al.* (74) conducted a retrospective study on seven patients who received T1 neurotomy for hand spasms, with an average follow-up time of (15.4 ± 10.3) months. At the last follow-up, the MAS of all seven patients decreased by two levels without

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decrease in muscle strength. And the house functional classification of hand function was improved in seven patients, three of whom restored active grip and daily use function of their hands, indicating significant efficacy of T1 neurotomy. Therefore, it may be a promising treatment, but further exploration is still needed.

Neuromuscular electrical stimulation (NMES)

Chen *et al.* (75) conducted a meta-analysis to explore the efficiency of NMES in children with spastic CP. A total of 26 articles (including 14 RCTs) were included and evaluated from the dimensions of standing, walking, running and jumping on the gross motor function scale. They found that NMES treatment significantly improved motor function in children, especially standing, running and jumping functions. In addition, Oh *et al.* (76) conducted a meta-analysis showing that the combination of NMES and MT for spasticity treatment could improve patients' walking speed, stride length and other indicators. However, no difference was observed in MASs. Due to its improvement effects on patients' function, NMES may be used as a supplementary treatment.

Brain–computer interfaces (BCIs)

Sieghartsleitner *et al.* (77) reported the successful use of functional electrical stimulation based BCIs to promote functional improvement and recovery in stroke patients, suggesting its efficiency. Similarly, Cervera *et al.* (78) also reported that BCIs could be an effective intervention for post-stroke upper limb rehabilitation through a meta-analysis involving nine studies (235 post-stroke survivors).

Transcranial magnetic stimulation (TMS)

Zhou *et al.* (79) conducted a review on the treatment of stroke using TMS. The reported results of TMS on functional improvement in patients are good, and it may be a good application direction.

Peripheral intermittent theta burst stimulation (piTBS)

El Nahas *et al.* (80) investigated the relieving effect of peripheral intermittent magnetic pulse stimulation on spasticity. The experimental group (25 individuals) received eight consecutive sessions of piTBS directly applied to the target spastic muscle, while the control group used a fake coil for comparison. The spasticity level of patients was evaluated before and after treatment, and the results showed that the improvement of upper and lower limb spasticity in the experimental group was significantly better than that in the control group. Therefore, piTBS is a treatment method that can reduce spasticity.

Deep brain stimulation (DBS)

Paro *et al.* (81) conducted a systematic review evaluating DBS therapy for post-stroke motor disorders, in which 53 patients were included. The most common DBS targets were the globus pallidus internus (n = 32), ventral intermediate nucleus of thalamus (n = 25) and subthalamic area/subthalamic nucleus (n = 7). The results suggested that DBS may be an effective treatment approach that can improve function, even years after stroke.

Transcutaneous spinal cord stimulation

Inanici *et al.* (82) treated six patients with spinal cord injuries using transcutaneous spinal cord stimulation. After treatment, the patients successfully recovered their hand and arm movement function. Some patients even regained hobbies such as playing guitar and oil painting that they had stopped for 12 years due to paralysis after treatment. Therefore, they believe that percutaneous noninvasive electrical stimulation of the spinal cord network can restore hand and arm movement and function.

Overall, T1 Neurotomy may be a potential surgery technique, but further exploration is still needed. The treatment methods of electrical/magnetic stimulation are mainly reflected in functional improvement, although some studies have also reported the effect of spasticity improvement. This may suggest that we can use them as supplementary treatment methods, but we still lack corresponding guidelines and parameter specifications, which is the direction that future scholars need to strive for (79).

Summary and outlook

We have reviewed the commonly used treatment methods for spasticity, including both surgical and nonsurgical approaches, to better promote further research on the treatment of spasticity. The fact is there is currently no ideal one that is close to perfection. In terms of nonsurgical treatment, ESWT may be a relatively better treatment because it does not produce too many adverse reactions, as seen with the use of BoNT-A, and its effect on improving spasms seems acceptable. But the long-term effectiveness of ESWT is also not perfect. In practical applications, it is also necessary to consider issues such as cost-effectiveness and setting appropriate parameters. The treatment method of electrical stimulation may serve as a supplementary therapy aimed at improving patient function, but further research is needed to explore optimal parameters and develop appropriate guidelines.

Current reports suggest that nonsurgical treatment methods and ITB do not have long-term efficacy, and there may also be many other drawbacks, such as catheter blockage, infection, repeated medication and

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drug withdrawal reactions (43). Our hospital has a large number of skilled and experienced hand surgeons, and we are committed to exploring effective methods for treating spasticity. Based on our own experience and a summary of previous studies, we still recommend surgery (except ITB) as the first choice for patients whose spasticity have affected their daily lives. Surgery (except ITB), as a permanent treatment method, is more effective in improving spasms, and in the long run, the treatment cost is lower than drug treatment. For example, the treatment cost of SDR may be much lower than the cost of ITB for 1 year (45). However, it should be noted that the specific surgical plan needs to be determined based on the patient's age, muscle tone and other factors (43).

Doctors and researchers need to further explore, whether it is providing high-quality evidence support for current treatment methods or exploring new possibilities for treating spasticity, to find a cost-effective treatment method that can simultaneously improve patients' spasticity and function.

ICMJE Statement of Interest

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the work reported.

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Author contribution statement

H-X Li helped in designing the framework, retrieving and screening literature and writing the manuscript. K Xu contributed in retrieving and screening literature and guiding manuscript writing. S-L Chen helped in providing expertise and guidance and reviewing the manuscript. S-F Wang helped in providing expertise and guidance and reviewing the manuscript. W-J Li helped in providing expertise and guidance and reviewing the framework and manuscript.

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