

Cerebral palsy: clinical care and neurological rehabilitation

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Cerebral palsy (CP) is defined as motor impairment that limits activity, and is attributed to non-progressive disturbances during brain development in fetuses or infants. The motor disorders of CP are frequently accompanied by impaired cognition, communication, and sensory perception, behavioural abnormalities, seizure disorders, or a combination of these features. CP is thought to affect three to four individuals per 1000 of the general population. The incidence, prevalence, and most common causes of CP have varied over time because of changes in prenatal and paediatric care. Medical management of children and adults involves care from primary-care physicians with input from specialists in neurology, orthopaedics, and rehabilitation medicine. Physicians should also work in conjunction with rehabilitation therapists, educators, nurses, social care providers, and schoolteachers. The focus of rehabilitation treatment has recently shifted to neurological rehabilitation in response to increasing evidence for neuroplasticity. This approach aims to improve development and function by capitalising on the innate capacity of the brain to change and adapt throughout the patient's life. As the life expectancy of individuals with CP approaches that of the general population, therapies must be developed that address the needs of adults ageing with disability.

Introduction

Cerebral palsy (CP) is the most common developmental disorder associated with lifelong motor impairment and disability. This disorder results from insult or injury to the brain before birth or in early childhood that causes neural connections to be formed in aberrant ways and leads to persistent abnormal limb strength, control, or both.¹ Clinical diagnosis of CP has traditionally been based on neurological examination, stable course, and the absence of an underlying genetic disorder. The neurological deficits correlate to some degree with the location of structural damage. In recent decades, there has been recognition of different causes of CP and altered demographic patterns.

Infants, children, and adults need effective rehabilitation therapies for neurobehavioural impairments that are grounded in neuroscience, and management strategies for primary neurological manifestations, such as epilepsy and spasticity, that are developed by neurologists. Advances in evidence-based approaches to clinical care have, however, been slow in CP, which has led to gaps in services and to opportunities to decrease morbidity, improve quality of life, and provide cost-effective care being missed. Some of these delays have been due to conflicting ideas about best care, and to differences in approaches between medical subspecialties. The realisation that neurodevelopment continues throughout the patients' lifespan has led to the theory that intensive, goal-directed rehabilitation therapies would substantially improve patients' motor function and their inclusion in the community.

Here, we review the features of multidisciplinary clinical management of CP. We provide a historical perspective of the disorder and describe the evolution in understanding of causes, diagnosis, and treatments over time. We discuss the increasing use of non-invasive management methods and developments in rehabilitation that capitalise on the innate plasticity of the nervous system, focusing on best practice now and in the future. We also present models for making the transition from

paediatric to adult care and for coordinating multidisciplinary services around the patient or the patient's family to provide comprehensive lifelong and preventive care.

Historical perspective

In ancient times CP was attributed to supernatural causes, such as God's wrath, witchcraft, and the "evil eye".² In the mid-19th century, CP was recognised as a medical disorder of infancy. Little³ described CP, which for some time was termed Little's disease, and proposed protracted labour as the cause. Osler⁴ later coined the term cerebral palsy. Freud⁵ attributed the disorder to brain injury from various causes, including prenatal events, and emphasised that extended labour was not the exclusive or even principal cause. Additionally, Freud conceptually united the various non-progressive motor deficit syndromes related to brain abnormalities of children into one nosology.⁵

In the 20th century in the UK, the Little Club was formed by clinicians with an interest in the terminology and classification of CP. Leaders moved the concepts and descriptions of CP forward, which led to greater efforts in related treatment services, advocacy, and research. For instance, MacKeith and Polani⁶ defined CP as "a persisting but not unchanging disorder of movement and posture, appearing in the early years of life and due to a non-progressive disorder of the brain, the result of interference during its development". Bax,⁷ a leading British paediatrician, reported and annotated a definition suggested by an international working group and concluded that CP was "a disorder of movement and posture due to a defect or lesion of the immature brain"; this definition is still widely used. Mutch and colleagues⁸ further modified the definition of CP and described it as "an umbrella term covering a group of non-progressive, but often changing, motor impairment syndromes secondary to lesions or anomalies of the brain arising in the early stages of development". This depiction led to the clinical diagnosis becoming focused on motor features and early damage to the developing brain.

At the start of the 21st century, advances in brain imaging, interest in testing treatments in clinical trials, and improved understanding of the various types of pathophysiology underlying CP led the international community to recognise that the disorder needed to be redefined. Comorbidities caused by early brain damage, including cognitive, sensory, and behavioural deficits, and the concept of restricted functional activity were included as important features. An international workshop was convened at the US National Institutes of Health in 2004, with participants from England, France, Belgium, Canada, and the USA, and a consensus was published¹ that was designed to meet the needs of clinicians, investigators, public health staff, and people with CP. The additional goal was to improve communication and collaboration worldwide. As a result of this effort, global collaboration and consistency in inclusion criteria for clinical research have improved. Additionally, activity and function are both routinely included as outcome measures for research interventions.

Clinical presentation and causes

The first clinical signs of CP can be seen any time before age 3 years.⁹ Onset is estimated to be seen in two neonates per 1000 livebirths;¹ population surveillance studies have shown a prevalence among school-age children in the USA of three to four per 1000.¹⁰ The reported incidence, prevalence, and most common causes of CP have varied over time because of changes in prenatal and paediatric care. Prenatal rubella is a striking example of a changing factor that has affected the epidemiology of CP. Through the middle of the 20th century, rubella in pregnant mothers was associated with a high rate of chronic rubella syndrome, which is characterised by congenital blindness, deafness, and CP, and was one of the most common causes of CP.¹¹ A rubella epidemic swept the USA in 1964, leading to a concerted collaboration between the Federal Government, academia, and industry to develop a solution. In 1969 a rubella vaccine was introduced and aggressively distributed; in 2006 no babies were born with chronic rubella syndrome in the USA.^{12,13}

Advances in neonatal care, such as treating neonatal jaundice and avoiding kernicterus, have contributed to the prevention of CP. By contrast, in developed nations, increasing numbers of premature and low-birthweight (<1500 g) babies that survive have led to a new generation of people affected with CP, probably because of vulnerability of the immature brain, especially in babies with intraparenchymal or intraventricular bleeds or periventricular white-matter abnormalities.^{14,15} The cause or causes of white-matter damage are debated, although inflammation is widely accepted as an important mechanism.¹⁶ Other causes in term infants and young children include infection, placental abnormalities, restricted intrauterine growth, and traumatic brain injury.

CP is classified according to the nature of the motor impairment revealed by neurological examination (paresis, hypertonia, hypotonia, dystonia, dyskinesia, and ataxia), the area of presumed cerebral dysfunction (pyramidal or extrapyramidal), and the parts of the body affected (eg, all four extremities, both legs, or one side of the body).¹⁷ Pyramidal lesions are most clearly associated with spasticity, hypertonia, and increased deep-tendon reflexes, and frequently with overflow reflexes (eg, crossed adductor spread) and an extensor plantar response. Extrapyramidal lesions are often associated with choreoathetosis and dyskinesias (and other forms of abnormal regulation of tone), abnormal postural control, and coordination deficits. Movement abnormalities are classified as athetoid, choreiform, or dystonic, alone or in various combinations. A consensus panel supported by the National Institutes of Health produced a report in 2006 that emphasised the primary role of functional activity restriction, which might include non-motor disabilities in function and behaviour.¹⁸

More than 80% of children with CP show neuroimaging abnormalities,¹⁹ most commonly isolated white-matter damage (associated with bilateral spasticity and ataxia).²⁰ Combined grey and white matter abnormalities correlate most often with hemiplegia, whereas isolated grey-matter abnormality is rare. In 17% of children with CP no imaging abnormality is seen.²¹ The increasing availability of sensitive techniques, such as diffusion tensor imaging, that can be used to detect and characterise aberrant brain pathways might make identification of CP possible before clinical signs appear.

Motor impairment of brain origin is present in all cases of CP, but other possible impairments related to brain damage include epilepsy, intellectual delays, and psychosocial abnormalities. Difficulty with swallowing and poor oromotor skills are among the first clinically identifiable symptoms in the neonatal period, and often precede more noticeable abnormalities, such as delays to developmental milestones (ie, sitting, rolling over, crawling, or walking). Ambulatory children with CP typically have spastic gait patterns. The investigation of methods to identify clinical signs of CP as early as possible is an important area of research. Abnormalities in motor patterns, such as cramped synchronised general movements, and the absence of fidgety or spontaneous movements at 2–4 months of corrected age in high-risk infants who were born prematurely are strong markers for CP, with reported sensitivity of up to 90%.^{21–24} These patterns are thought to be more predictive of CP than swallowing difficulties and poor oromotor skills.^{21–24}

Neurological complications

Neurologists should be aware of various neurological issues that might accompany the primary motor impairments of CP, particularly seizures, cognitive

	Neurological implications	Functional implications	Medical and surgical complications
Cortical (bulbar or spinal) tract damage in infancy	Weakness, motor-function abnormalities, spasticity, oromotor dysfunction	Activity limitations, spastic gait, weight-bearing asymmetries, impaired upper-limb functions, limited independence in activities of daily living, and impaired feeding, nutrition, articulation, and communication	Uneven limb length, osteoporosis, scoliosis, musculoskeletal pain, impaired growth and development
Cortical damage	Seizure disorder	Potential for impaired cognitive performance and need for medication	Antiepileptic medication might promote osteoporosis
Basal ganglia damage	Dystonia, choreoathetoid movement	Impaired motor performance	Pain and cervical stenosis in adulthood
Cortical and periventricular leukomalacia	Cognitive impairment, psychosocial impairment	Impaired educational and vocational opportunities	Depression, isolation

Table 1: Neurological processes and consequences in cerebral palsy

disturbances, and pain (table 1). Management does not generally differ from that in other patients, although adverse effects of medication might be more troublesome.

Seizure disorders are seen in up to a third of individuals with CP.²⁵ Those with spastic quadriplegia or hemiparesis seem more likely to have seizures than children with spastic diplegia or ataxic CP, possibly because of a higher percentage of symptomatic epilepsies, such as focal seizures or status epilepticus. Positive prognostic factors for remission of seizures include normal intelligence, a single seizure type, control of seizures with monotherapy, and normal MRI.²⁶

Cognitive deficits are seen in around 50% of people with CP.²⁷ Presumptions about intellectual abilities might prevent some patients with CP from receiving adequate educational opportunities. Learning disabilities and sensory disorders are especially common in conjunction with a seizure disorder.²⁸ Deficits in visual-spatial and analytical capabilities might be present despite excellent language skills. Children must be assessed thoroughly to ensure that communication difficulties can be distinguished from cognitive dysfunction and that vision or hearing loss are properly addressed. In addition to problems with visual acuity, children with CP are at increased risk of cortical visual impairment and for strabismus, which can lead to amblyopia.

Pain is generally neglected in chronic complex medical conditions. Frequent causes of pain in CP are muscle spasm, muscle strain, orthopaedic issues, undetected dental caries, skin breakdown, constipation, which is common in nonambulatory patients, and gastric reflux.

Management

A summary of the general principles of multidisciplinary management of CP are provided in table 2.

Transition from paediatric to adult care

Throughout the 20th century, CP was managed by developmental paediatricians and orthopaedic surgeons. This approach continues to some degree to the present day. The emphasis was placed on tendon release and transfer and joint revision to promote walking,

realignment of joints, and increased comfort. Decisions about whether to do surgery and what surgical approach to use were based on evidence from clinical case reports and the individual surgeon's judgment. The effects of changes in gait pattern as patients grew and the transition of patients from children into adults were generally not taken into account. Many people with CP, however, now live well into adulthood. Patients in their 20s, 30s, and 40s frequently try to avoid changing specialists and continue to seek care from their treating paediatrician. Furthermore, because CP has traditionally been viewed as a disorder of childhood, adult specialists in primary care, internal medicine, and neurology were not taught about CP management in residency training programmes. A new model of care that takes into account the increasing life expectancy of individuals with CP needs to be developed.

The choice of interventions in children should ideally be informed by evidence of the outcomes and effects in adults who have undergone the procedures, but long-term outcomes associated with childhood surgeries have not been well documented. Natural history studies investigating life stages, specific challenges, and physical or health-related quality of life in terms of daily activities are required. The care provided should evolve to meet the patient's needs throughout his or her life.

Mixed populations of adults of various ages and abilities who self-reported deterioration in mobility over time associated with fatigue and hip and lower-back pain have been assessed.^{29,30} Specific types of pathophysiology were difficult to separate from the decrease in muscle mass associated with natural ageing. By contrast, however, ageing with an underlying motor disability was linked to complications associated with an imposed sedentary lifestyle (eg, obesity, early-onset type 2 diabetes mellitus, dyslipidaemia, etc).³¹ Pain is typically related to osteoarthritis of the spine and hips, associated with gait deviations, postural abnormalities, and spasticity leading to joint misalignment and overuse. Quality of life in adults with CP is associated with level of education, employment status, and access to health care.^{29,30}

	Rehabilitation*	Medical therapy†	Therapeutic team approach‡
Motor weakness	Strengthening, task-specific intensive therapy, functional neurostimulation	Assessment of joint alignment and avoidance of joint overuse and tendon strain and rupture, preventive approach against painful syndromes later in life	Educate patient and family to promote functional activities at home and in the community
Tone abnormalities	Stretching, task-specific practice, functional neurostimulation, serial casting, orthotic devices	Oral medicines (baclofen and tizanidine), botulinum toxin injections, nerve blocks, intrathecal agents, treatment of disorders such as scoliosis and tendon contractures by orthopaedic surgery	Educate patient and family about positive and negative effects of treatments and interventions, elicit feedback to monitor success, encourage self-directed stretching and use of prescribed devices
Cognitive impairments	Neuropsychology and speech or language therapy after assessment of extent and precise nature of deficits (eg, attention vs memory)	Consider pharmacological treatment of attention deficits, monitor effects of other medications on cognition	Work with family and school on an individualised educational plan and adaptive communication devices
Seizure disorder	..	Diagnose and treat as for patients without cerebral palsy	Educate patient and family about complications and risks
Psychosocial disorders	Neuropsychology, speech therapy, occupational therapy	Psychiatric assessment of affective and social disorders and counselling and pharmacotherapy as appropriate	Empower family to use techniques for engaging patient and advocating for appropriate measures in school and in the community
Oromotor impairment	Speech therapy, occupational therapy	Nutritional and enteral supplements	Family engagement and education

*Physical therapy, occupational therapy, speech therapy, nursing care, social work, and psychology. †Neurology, paediatric care, internal medicine, physiotherapy, and psychiatry. ‡To promote a patient-centred or family-centred approach.

Table 2: Management approaches for cerebral palsy

Patient-centred and family-centred medical home models

The US medical care delivery model is currently undergoing a transformation that could substantially improve the availability and continuity of care for people with CP. Concerted efforts have been made to apply to public health well documented strategies and new incentives outlined in the Affordable Care Act of 2010.³² Reimbursement for services will be tied to health outcomes, access, patient-centred approaches, and continuity of care through a patient-centred medical home model. This team-based model of care consists of a personal physician who provides continuous care, including management of chronic illness, and coordinates care provided by other team members throughout a patient's lifetime to ensure optimum health outcomes. Emphasis is placed on participation by the patient and his or her family in therapeutic decisions, taking into account their experiences. The programme would include management of primary, secondary, and tertiary complications of chronic disorders, preventive care, and maintenance of functional activity.³³ Clinical services would be coordinated from a central location to create a simplified, streamlined plan of care. This approach contrasts with the traditional medical model of a physician or team of physicians dictating care to patients and their families.

Access to rehabilitation therapy and even to primary medical care for patients with CP worldwide can become difficult after age 18 years, possibly because CP continues to be seen by the clinical community as a paediatric diagnosis; the life expectancy in previous generations was much lower than it is currently. Children and adults

need comprehensive, coordinated care focused on preventing complications (malnutrition, skin breakdown, pain) and promoting improved neurological function, which could ultimately improve health, quality of life, and access to education and vocational opportunities. Ideally, care should be provided by a consistent team that can assess and treat the primary and secondary effects of CP as well as common comorbidities, and provide primary and specialty medical care, rehabilitation, psychosocial treatment, and support for the patient and family (table 1).

For children and some adults with CP, family-centred care is an accepted component in achieving maximum independence, especially for patients with cognitive impairment. The family-centred approach respects a family's uniqueness, transcends cultural boundaries, and recognises that the family unit is the most important and constant context for an individual with disability.^{34,35}

Integration of medical, neurological, and rehabilitative care

Best outcomes, and, therefore, lower costs, will be realised if clinical care is organised, evidence-based, and multidisciplinary, ideally in the patient-centred or family-centred model. The maintenance of health in the context of primary and secondary neurological complications must be a fundamental goal. The monitoring of growth, screening of hearing and vision, and maintenance of appropriate immunisations are all important preventive strategies. The optimum team would include a primary-care physician experienced in neurological rehabilitation, a psychologist, a physical therapist, an occupational therapist, a speech therapist, a social worker, and a schoolteacher.

Physical therapy should focus on gross motor skills, strengthening, and the provision of mobility devices and other equipment needs. Occupational therapy should concentrate on upper-extremity functions, such as feeding, dressing, toileting, and bathing, and use of adaptive technologies and equipment. Speech and language therapy should address articulation, oromotor deficits, language skills, readiness for school, and use of communication systems. All the rehabilitation therapists need to coordinate and regularly to communicate their observations to the primary medical coordinator.

Stretching and flexibility exercises remain integral components of most physical therapy programmes for children with CP, despite inconclusive evidence for their effectiveness. Wiart and colleagues³⁶ posited that active community-based recreation programmes that incorporate flexibility would be more successful in improving mobility than passive stretching, because evidence has indicated that contracture development could be related to muscle atrophy. Regular exercise is necessary for the health of children and adults, but in those with CP the ability to exercise is adversely affected by motor impairment. Physical therapists can develop adaptive exercise programmes that build muscle mass and increase endurance; numerous studies have shown that physical therapy improves endurance, strength, and gross motor function, but more studies are needed to assess the effects of the intensity of therapy and the use of different techniques, such as bodyweight-supported treadmill training.³⁷ Butler and colleagues³⁸ did a systematic review of randomised trials in school-aged children to assess whether cardiovascular and strengthening exercises are beneficial in CP. Although evidence about the functional benefits of cardio-respiratory training was limited, aerobic fitness did seem to improve. In an earlier systematic review, however, the same investigators had concluded that strengthening exercises did not improve motor function.³⁹

In adults with subacute or chronic stroke, intensive, task-specific, and engaging exercise that motivates the patient improves recovery.⁴⁰ In a study of ambulatory children with CP, repetitive locomotor training with an electromechanical gait trainer was compared with conventional physical therapy. Significant improvements were seen in walking speed, stride length, and joint kinematics.⁴¹ Studies of techniques such as constraint-induced movement therapy and other forms of therapy that encourage intensive, goal-directed use of the more impaired upper extremity have also been associated with significant improvements in motor function in children with CP (see below).⁴²⁻⁴⁴

Speech and language therapy includes interventions to improve feeding; such efforts often require skills and input from other members of the clinical team, particularly occupational therapists and rehabilitation nurses. Thus, eating behaviour, caloric intake, and

growth should be monitored closely. If failure to thrive is suspected, treatment by an interdisciplinary feeding team might be necessary.⁴⁵ Swallowing issues can arise from various causes, from oromotor dysfunction to sensory aversions to learned behaviours. Various tests, such as modified barium swallow or flexible endoscopic assessment of swallowing with sensory testing, might be necessary to ensure the safety of oral feeding; in some cases percutaneous gastrostomy could be considered. Improved nutritional status, particularly leading to fat-free mass gain, has a positive effect on growth and motor skills in children with CP.⁴⁶

Assessments of changes in functional independence should be done throughout the patient's lifespan to ensure efficacy of clinical care. An individual's functioning in the community differs markedly from estimates of ability based on a brief examination; an individual who can walk a few steps down a corridor might be unable to navigate long, busy school corridors or uneven terrain.

Management of neurological complications

The neurological processes and manifestations that must be assessed and managed in patients with CP are shown in table 2. Management of epilepsy in children or adults with CP does not differ from that in people without CP. For cognitive and neuropsychological impairments, clinicians must work closely with educators to help identify teaching methods that are consistent with the deficits.

Hearing screens with otoacoustic emissions can be done before neonates leave hospital.⁴⁷ Other methods that can be used later in life include brainstem auditory evoked potentials and behavioural tests of hearing thresholds for different tones. Vision screening is not done routinely in infants, although tests that correlate well with visual acuity, such as Teller acuity cards, are available.⁴⁸ Aids that improve function and inclusion in the community include spectacles, hearing aids, communication devices, and adaptations to enable use of computers.

Spasticity should not be treated unless it reduces muscle function or causes secondary complications, such as orthopaedic disorders and pain, or interferes with care. If treatment is required, physical therapy, medication, surgery, or a combination of these approaches might be appropriate. Spasticity can be alleviated to a small degree with oral medications such as dantrolene, baclofen, diazepam, and tizanidine.⁴⁹ Injections of botulinum A toxin inhibit the release of acetylcholine from the presynaptic site at the muscle nerve junction. The effects of this treatment last 3-5 months and, therefore, repeated treatments are generally necessary. Botulinum A toxin has also been used to treat focal dystonias and rigidity in hemiplegic or diplegic spasticity.⁴⁹ Complementary approaches that increase relaxation (eg, guided imagery, breathing techniques, and biofeedback) might be helpful,⁵⁰ but substantial evidence from randomised, controlled trials is unavailable.

Orthopaedic care

Orthopaedic surgical interventions to alleviate severe mechanical impairments might be appropriate, although little strong clinical evidence is available to guide decision making; data from case series are mainly descriptive. The main complications of CP that can be treated surgically are joint dislocations and deformities (particularly of the hips), scoliosis, and contractures. Tendon transfers are done to improve functional grip and foot clearance for walking.^{51–54} Surgical intervention might be indicated in cases of substantial hip subluxation.⁵¹ Heel-cord tightening might be better managed conservatively with serial casting than with surgical lengthening.^{55,56}

Femoral and tibial osteotomies can be considered for dislocation or rotational deformities of the lower extremities, and might improve gait.⁵¹ Computerised gait analysis can be informative before surgical intervention to improve ambulation. Gait analysis is particularly helpful in determining the causes of crouch gait (equinus *vs* hamstring tightness, lever arm dysfunction, or both), intoeing (femoral *vs* tibial torsion), and pes varus (anterior *vs* posterior tibialis dysfunction), and can even be useful in cases of single-level gait issues.^{57–59}

Neuroplasticity

The integration of technological advances into care is directing research trends in CP. Neurorehabilitation in general, and particularly in CP therapeutics, aims to capitalise on a growing appreciation of brain plasticity throughout the lifespan and the possibility that this feature can be harnessed for therapeutic gains. Holt and colleagues⁴⁵ comprehensively reviewed the effects of early interventions to improve brain development. They concluded that exposure to enriched sensory environments and a nutritious diet are associated with improved cognitive outcomes and increased brain growth for infants with perinatal brain damage.

Early lesions and defects of the motor cortex and periventricular white matter are associated with reorganisation of the corticospinal system during subsequent development.⁶⁰ Tian and colleagues⁶¹ used functional near-infrared spectroscopy to assess laterality of brain activation in children with hemiplegic CP in comparison with that of healthy controls. Contralateral activation during motor tasks was consistently present in controls, but children with congenital hemiparesis showed ipsilateral and bilateral activation patterns.

In healthy human fetuses, corticospinal tract development advances from the cervical cord from 24 weeks' gestation onwards, and spinal neurons are progressively innervated from 27 weeks' gestation until birth.^{62,63} In healthy infants, transcranial magnetic stimulation motor evoked potential latencies have been used to study the timeline of corticospinal development and reorganisation. During the first 24 months after birth transcranial magnetic stimulation latencies steadily

decline, which correlates with progressive myelination. By contrast, motor thresholds are low at birth, which implies that human babies are born with many corticospinal axons; low-intensity transcranial magnetic stimulation can, therefore, elicit a substantial motor neuron response. Motor thresholds increase rapidly during the first 3 months after birth but progressively decline over the remainder of the first 24 months.⁶⁴ This finding implies that some corticospinal connections present at birth are not permanent and withdraw during the following 3 months, and that axonal withdrawal and corticospinal connectivity reorganisation continue until age 2 years.⁶⁵ Healthy neonates have low-threshold-equivalent ipsilateral and contralateral motor evoked potential responses to transcranial magnetic stimulation. By 24 months, however, ipsilateral motor evoked potential thresholds increase and latencies are longer than those in contralateral responses.⁶⁴

Early lesions of the motor cortex correlate with different patterns of subsequent nervous system development.^{60,62–67} An important difference is the persistence of low thresholds for inducing ipsilateral motor evoked potentials from the non-lesioned hemisphere while the threshold for inducing contralateral and ipsilateral motor evoked potentials from the lesioned hemisphere steadily increases. The term competitive withdrawal is used to describe loss of connectivity in the lesioned hemisphere leading to the intact hemisphere gaining control of both sides of the body. To a substantial degree, these adaptations promote more motor function for individuals with brain lesions, but in most cases abnormalities remain in posture, tone, gait, and dexterity that lead to disability. Therefore, although declining ipsilesional contralateral connectivity and persistent contralesional ipsilateral connectivity are beneficial, this situation is not optimum. Whether therapeutic interventions can shape these adaptive neurodevelopmental processes is, therefore, an important question.

Advances in neuroscience suggest that the CNS has some plasticity and the potential to reorganise throughout the entire lifespan, rather than merely during a short period of development. Studies in primates and human beings suggest that activity-dependent plasticity takes place in the motor cortex.^{68–70} The concept that intense, task-specific exercises capitalise on the potential plasticity of the CNS and thus improve motor recovery has led to the development of several successful interventions for adults with acute and chronic stroke.⁴⁰ Examples are constraint-induced movement therapy, in which the stronger upper extremity is constrained to force practice in using the weaker arm for tasks,⁷¹ and bodyweight-supported treadmill training.⁷² These findings have led to renewed efforts to identify CP early and to assess the effect of task-specific neurological rehabilitation in individuals with this disorder; preliminary evidence indicates that these interventions could improve function for children with CP.^{42–44,71–77} Randomised trials to compare

constraint-induced movement therapy with traditional therapy for CP are increasing in number.⁷⁴ Constraint of the unaffected arm, even without additional rehabilitation, can improve function in the affected arm in children with hemiplegic CP.⁷⁵ Additionally, training improved bimanual coordination in children aged 5–9 years with hemiplegic CP, compared with coordination in children who received no physical therapy.⁷⁶ Bodyweight-supported treadmill therapy uses intense (speed-focused), task-specific activity to improve locomotor function. In one study, a programme of 12 sessions resulted in slight increases in the walking speed of children with CP and moderate to severe disabilities.⁷⁷

Robot-assisted activity can improve upper-arm function in adults with impaired mobility after stroke.⁴⁰ The improvements seem to be long term and better than those achieved with usual care, at a similar cost.⁴⁰ Robotic therapy might increase functional strength and improve isolated movements, because consistency of assistance can be maintained, intensity and difficulty can be set according to the patient's improvement, and virtual reality interfaces can improve the patient's motivation, which could enable targeting of the activities of daily living. Preliminary data suggest that this type of therapy also improves motor function in the upper and lower extremities that are caused by CP or other acquired brain injuries.^{78,79} These data suggest that use of such interventions in children with CP can improve movement and function as they do in adults with stroke.

Other technological advances might promote neurological rehabilitation in patients with CP. Virtual reality has been incorporated into physical interventions to increase motivation and perhaps could take advantage of neuroplasticity.⁸⁰ Engineering developments in integrated circuits, wireless communications, and physiological sensing have enabled the creation of miniature, lightweight, ultralow power, intelligent monitoring devices that can monitor motor activities and transmit information bidirectionally between patients and therapists. Interventions can, therefore, be delivered at appropriate times throughout the day. Such devices might lead in the future to health and safety monitoring and rehabilitation being based mainly or wholly at home, in the community, or both.⁸¹ Bloom and colleagues⁸² studied an electromyogram-initiated device that delivers vibratory stimulation to the forearm muscles for up to 5 h throughout the day, and reported significant improvements in upper-extremity function.

Such preliminary studies are interesting, but there are too few rigorous clinical trials to provide an evidence base and to support routine use of these new methods outside trials. Additional, well controlled, randomised trials are needed to establish efficacy and to define the most appropriate roles for new technologies in physical rehabilitation interventions for children with CP.

Search strategy and selection criteria

We searched PubMed, without date limits, with the following terms: "cerebral palsy [and] etiology", "therapy", "diagnosis", "constraint-induced therapy", "robotic rehabilitation", "mass practice", "learned disuse", "body-weight supported treadmill training", and "medical home". We judged these terms to reflect the major current issues in clinical research and practice related to cerebral palsy. We selected English-language articles, primarily according to historical interest and relevance to clinical neurology practice, especially those that provided evidence in support of recommended practice or reported therapeutic research.

Knowledge of the time course and elemental processes in the development of the corticospinal system and its plasticity throughout life is essential for the creation of stage-specific rehabilitation strategies. Specialists in neurology, rehabilitation, and orthopaedics will need to be involved in the design of interventions that combine spasticity management and motor practice. Coupled with early diagnosis, evidence-based therapeutics will lessen the burdens associated with CP.

Conclusions

CP is a prevalent, disabling condition. Neurologists treating children and adults must be familiar with the clinical manifestations and common comorbidities, and with the optimum treatments to effectively participate in the multidisciplinary management team. In addition to management of weakness, spasticity, cognitive dysfunction, nutritional issues, and seizures, care teams must address rehabilitation strategies to maintain and improve function. Application of evidence-based methods, particularly constraint-induced therapies, will ensure maximum gains in children and adults. Research suggests that brain plasticity is important to the pathophysiology and treatment of CP throughout a patient's life. This feature has directed research into functional recovery, and rehabilitation therapies are being developed that aim to capitalise on neuroplasticity. Specific pharmacological and non-pharmacological approaches to rehabilitation of individuals with CP must also be assessed in rigorously designed clinical trials.

Contributors

MLA, SM, and RMK did the literature searches. DK reviewed the literature, outlined the content of the article, and provided an update about neurodevelopmental anatomy and physiology in fetuses and infants and implications for interventions. JM provided the information on management of epilepsy, spasticity, and other comorbidities. SM, TALW, and SAR were involved in the writing of the manuscript. MLA coordinated and edited all contributions from other authors.

Conflicts of interest

We declare that we have no conflicts of interest.

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