Motor Behavior and Neural Changes Following Perinatal and Adult-Onset Brain Damage: Implications for Therapeutic Interventions
Charles T Leonard


The online version of this article, along with updated information and services, can be found online at: http://ptjournal.apta.org/content/74/8/753

**Collections**
This article, along with others on similar topics, appears in the following collection(s):
- Anatomy: Central Nervous System and Neuromuscular System
- Cerebral Palsy
- Cerebral Palsy (Pediatrics)
- Motor Development Perspectives
- Traumatic Brain Injury

**e-Letters**
To submit an e-Letter on this article, click here or click on "Submit a response" in the right-hand menu under "Responses" in the online version of this article.

**E-mail alerts**
Sign up here to receive free e-mail alerts
Motor Behavior and Neural Changes Following Perinatal and Adult-Onset Brain Damage: Implications for Therapeutic Interventions

This article provides information pertaining to recent scientific findings regarding neural and motor development and the effects of brain damage on that development. The article is intended to provide the clinician with new information that will assist in patient assessments and the establishment of therapeutic interventions. Clinical and scientific issues pertaining to perinatal and adult-onset brain damage are discussed. [Leonard CT. Motor behavior and neural changes following perinatal and adult-onset brain damage: implications for therapeutic interventions. Phys Ther. 1994;74:753-767.]

Key Words: Brain damage, chronic; Cerebral palsy; Motor activity; Neurophysiology/neuroanatomy; Perinatology.

Clinicians working in neurological rehabilitation often observe differences in the motor behavior of patients with perinatal brain damage and those with adult-onset brain damage. The time at which brain damage occurs and the extent and location of damage are important factors contributing to behavioral outcomes. The initial section of this article will outline some early developmental neural changes that are of particular clinical relevance. Subsequent sections will discuss issues pertaining to motor behavior, spasticity, and therapeutic interventions.

Throughout this article, the terms “hypertonia” and “spasticity” are used. Tone is defined clinically as a muscle’s velocity-dependent resistance to passive stretch. Muscle tone appears to reflect the relative influences of the physical inertia of the extremity, the mechanical-elastic characteristics of muscular and connective tissues, and the reflexive drive to the muscle (stretch reflexes). Hypertonia is one characteristic of spasticity. The term “spasticity,” however, refers to a syndrome that encompasses a constellation of signs and symptoms. There continues to be some debate regarding the components that comprise the clinical definition of spasticity. Typically, however, spasticity is defined as a motor disorder characterized by velocity-dependent hypertonia, hyperactive tendon reflexes, and clonus. Abnormal patterns of muscular coordination, reflex irradiation, reduction of the threshold angle at which the stretch reflex is elicited, abnormal muscular co-contraction during voluntary movement, hypersensitivity to various sensory input in addition to muscle stretch, paresis, and disruptions in automatic postural reactions are all associated with the spastic condition. The degree to which these variables contribute to movement dysfunction varies among individuals and among diagnoses.

Principles of Ontogenetic Neural Development

For the purposes of this article, the following definitions will be used. Perinatal refers to the period before, during, or shortly after birth. Neonatal refers to the period immediately after birth; for humans, the term neonate generally refers to the first month after birth. The perinatal nervous system is considerably differ-

CT Leonard, PhD, PT, is Associate Professor and Research Director, Motor Control Research Laboratory, Physical Therapy Department, The University of Montana, 026 McGill Hall, Missoula, MT 59812 (USA).

The author's studies cited in this article were supported by The American Academy for Cerebral Palsy Research Foundation, The National Institutes of Health (4X-5925), The Swedish Medical Research Foundation, and The University of Montana.

This article was submitted May 21, 1993, and was accepted January 24, 1994.
ent from that of the fully mature nervous system. For instance, myelination is not yet complete, neurons within the brain have not completely differentiated, there is an over-abundance of neurons in certain areas such as the spinal cord, and some corticofugal projections (projections from the cerebral cortex to the brain stem and spinal cord) project to inappropriate targets (ie, locations at which connections are not found in the adult animal). These neural differences provide part of the basis for the differences in motor behavior that are observed following perinatal brain damage as compared with those found after adult-onset brain damage. Although a complete review of ontogenetic neural development is beyond the scope of this article, those events that are applicable to human clinical experimentation will be discussed.

The development of the vertebrate nervous system, including that of humans, involves regressive as well as progressive neural events. Some of these events are genetically predetermined, whereas others are influenced by experience and afferent activity. Progressive events include neural proliferation, synaptogenesis, myelination, cell migration, axonal growth, and the formation of complex neural pathways. Regressive events include cell death and retraction of neural projections. Regressive events are just beginning to be defined and deserve further discussion here, as these events are of potential clinical significance.

Naturally occurring neuronal death and axon retraction are major features of neurogenesis. During perinatal development, there are various periods during which neural degeneration and death occur in a variety of neural structures, including at the neuromuscular junction, spinal cord, brain-stem nuclei, and cerebral cortex. Muscle fibers of humans are multiply innervated early in development. Axon retraction occurs approximately during the eighth week of gestation so that each muscle fiber is then innervated only by fibers from a single axon. Axon retraction involving the cortex and cerebellum is more prolonged. Axon retraction of these structures begins by the third trimester and extends into the first few postnatal years in humans. There is approximately a 50% loss of neurons during early development in most of the brain structures studied. Thus far, cell death and axon retraction appear to be selective processes that are used for the matching of neural populations with appropriate targets. Competition for a limited quantity of trophic substances located within each target area appears to limit the number of projections that can be supported. In this way, functionally redundant neurons and projections within a target area are eliminated. There is also selective elimination of neurons whose axons grow into inappropriate target areas.

The widespread distribution of neural projections may either be a function of an excessive number of neurons or excess axonal collateralization from individual neurons. The presence of neural projections in excess of those normally found in the adult is referred to as "neonatal neural exuberance." The retraction of these redundant or inappropriate projections and the establishment of refined pathways appear to be related to synaptic activity. That is, the establishment of correct neural connectivity depends on using the pathways.

The apparent dependence of neural connectivity on afferent input (incoming projections from multiple sources including, but not limited to, sensory input) during early development is of potential clinical importance, especially as it relates to early physical therapy intervention. A child with damage to motor areas of the brain will be restricted in his or her movement repertoire and experience. This lack of activity results in restriction of afferent input and may cause further deficits in the development of cortical and subcortical morphology structures. Intensive early physical therapy with an emphasis on stimulating purposeful movement, and thereby afferent inflow, may lessen these effects. This premise will be discussed further.

**Differences in Motor Behavior Between Brain Damage Occurring Perinatally and That Occurring as an Adult**

Nonhuman animal research has shown that perinatal brain damage generally results in less severe motor behavior consequences than does similar damage to the adult brain. Exceptions, however, have been reported. This greater recovery or sparing of function is termed "the infant lesion effect." Although it is generally agreed that perinatal brain damage does not affect motor behaviors as severely as adult-onset brain damage, few studies have examined which motor behaviors are differentially affected by the timing of the insults. Studies using animal models were undertaken to examine these issues. Abnormal postural reflex reactions and disorders of voluntary movement are commonly assessed and treated by therapists. It was of clinical interest to determine whether postural reactions and complex voluntary goal-directed movement were affected similarly following neonatal or adult-onset brain damage.

Cats receiving surgical ablation of the sensorimotor cortex at birth (neonatal operates) achieved better return of postural reflex responses and goal-directed movement compared with animals receiving similar sensorimotor cortical ablations as adults (adult operates). For instance, neonatal operates' postural righting reactions were quicker and consistently present, and they were able to cross complex runways (containing holes and obstacles) with fewer errors compared with adult operates. Neonatal operates were also able to incorporate spared reflex responses into complex motor acts. Although their movement repertoire was not as severely affected as that of adult operates, neonatal operates were more hyperkinetic during locomotion. A striking example of the differences between neonatal operates and adult operates is provided by neonatal operates' response to such extrinsic factors as the placement of visual stimuli.
Figure 1. Forelimb lateral placing responses of fully mature cats that had received sensorimotor cortical lesions at birth (neonatal operates) or as adults (adult operates). A dyne is a unit of force (dyne = grams x centimeters per second per second). Low-threshold placing (<980 dynes) was abolished in the right forelimb (RFL) of adult operates. In contrast, neonatal operates exhibited low-threshold placing responses about 20% of the time. The presence of low-threshold placing following neonatal but not adult-onset sensorimotor cortical lesions is an example of the infant lesion effect. (Reprinted with permission.)

operates was the recovery in neonatal operates of a postural reflex known as "low-threshold tactile placing" (Fig. 1). Tactile placing is a response that causes an animal to withdraw its limb from a stimulus in a stereotyped manner. Testing of this response is similar to procedures for testing upper- and lower-extremity placing withdrawal of the human infant. This response is a cortically dependent reflex in an adult animal and is permanently abolished following damage to the sensorimotor cortex in the adult.1,58

The sparing of tactile placing represents an example of neonatal developmental plasticity and served as the basis for studies with human infants.8,10,59 Tactile placing responses change during development in such a way as to suggest a change in anatomical substrates (ie, the anatomy that underlies the behavior) with maturation. Tactile placing of cats is present at birth. The sensorimotor cortex is unnecessary for placing in infants but is required in adults. Bradley et al40 reported that placing did not develop if the spinal cord was transected in 10- to 14-day-old cats. Robinson and Goldberger41 reported similar findings but found that placing did develop if spinal transections were made at the day of birth. These studies1,40,41 indicate that cortical mediation of placing develops postnatally and that placing can develop as a spinal reflex if cortical influences are eliminated prior to the development of cortical mediation of tactile placing. The findings indicate that behavioral outcomes are dependent on the age of the animal at the time of central nervous system (CNS) insult. These studies1,40,41 together with studies showing dramatic neural change with development18-21 suggest that the mechanisms mediating recovery following neonatal CNS damage and those mediating recovery in the mature animal are not identical.

Certain motor behaviors (eg, locomotion, hand grasping) may be unaffected at the time of the lesion in infants, but they then display deficits during subsequent development. This is termed "growing into deficit." Growing into deficit is further evidence that at different stages of perinatal development, one type of behavior may be subserved by different neural structures. Recovery of function appears to depend on the stage of development of the damaged pathway and also on the stage of development of undamaged pathways.2,21,33

In summary, several concepts have emerged from nonhuman animal studies: (1) Cortical influences on motor behavior are not necessarily observed at birth but emerge over time;2,21 (2) certain segmental reflexes that can function autonomously in the neonate become increasingly dependent on cortical inputs over time;2,21,41 (3) critical periods exist whereby damage to various parts of the CNS...
will have different behavioral effects depending on whether the damage occurs prior to or after this critical period.\textsuperscript{2,21,40,41} (4) the maturity of a pathway at the time of the lesion and the maturity of undamaged neural structures to mediate compensatory processes play critical roles in the recovery process.\textsuperscript{2,20,21,42} and (5) growing into a deficit is a common occurrence following perinatal brain damage.\textsuperscript{2,21,33}

**Neural Changes Associated With Perinatal and Adult-Onset Damage to the Sensorimotor Cortex**

Following damage to the sensorimotor cortex, anatomical substrates used for recovery of function may include undamaged cerebral cortical areas, motor control centers within the brain stem, basal ganglia, cerebellum, or changes in spinal cord projections. For example, as has been noted, placing, a cortically dependent reflex in adult cats, was spared in neonatal operates. Compensatory changes in neonatal operates' cortical projections, therefore, were theorized to be responsible for the spared placing.\textsuperscript{1}

Following damage to the sensorimotor cortex in newborn or adult cats, compensatory pathways might originate from the parietal cortex adjacent to the lesion or in the contralateral, intact sensorimotor cortex, or both. A series of experiments were performed to examine cortical efferent projections from these locations following neonatal or adult sensorimotor cortical lesions.\textsuperscript{21} These same cortical efferents were also examined in normal adult cats and normal 1-day-old animals. Methodological and data analysis procedures are explained in detail elsewhere.\textsuperscript{21}

Injections of neural tracers into the brain of cats permitted mapping of corticofugal projections. Following injections of a tracer into the parietal area surrounding the lesioned sensorimotor cortex or the contralateral, intact sensorimotor cortex of adult operates, there were no discernable differences in the size or location of projections from that of normal adult animals. There were also no obvious changes in the projections from the remnant parietal cortex in neonatal operates. The contralateral, intact sensorimotor cortex of neonatal operates, however, displayed considerable change. In normal adult cats, the corticothalamic and corticorubral pathways were strictly ipsilateral (Fig. 2c). In neonatal operates, these pathways had strong bilateral projections (Fig. 2b). These bilateral projections could either have sprouted from undamaged cortical regions or be a retention of exuberant projections. Injections into the sensorimotor cortex of normal 1-day-old cats support the later premise. On the day of birth, corticothalamic and corticorubral projections exhibited dense bilateral projections (Fig. 2a). These data provide support that one mechanism mediating the infant lesion effect is an arrest of anatomical development that involves the abnormal retention of neonatal neural exuberance. Other neuroanatomical changes also occur that indicate that perinatal brain damage has considerable impact on both progressive and regressive events.

The anatomical alterations that result from perinatal but not adult-onset brain damage to the motor cortex include (1) increased distribution of cells contributing to the corticospinal tract (ie, neurons sending projections to the spinal cord are found throughout the cerebral cortex rather than primarily isolated to the sensorimotor cortex),\textsuperscript{43} (2) sprouting of the ipsilateral corticospinal tract,\textsuperscript{44} (3) alteration in the distribution of callosal projections,\textsuperscript{45} (4) retention of bilateral corticorubral projections,\textsuperscript{21} (5) retention of bilateral corticothalamic projections,\textsuperscript{21} (6) an increase in the size of surviving cells within the ventrolateral nucleus of the thalamus,\textsuperscript{21} and (7) survival of late-developing pathways.\textsuperscript{42}

The studies with nonhuman animals discussed thus far provide evidence that the age of the developing brain at the time of an injury could be a major factor affecting functional outcomes. Various CNS structures have different critical periods. If damage occurs prior to or after this period, a different clinical presentation could result. Studies\textsuperscript{8,39} have been initiated to determine whether these principles apply to humans and are of clinical significance. These studies have examined the role of higher brain centers in human voluntary movement and locomotion. Studies\textsuperscript{10} have also examined whether neural exuberance exists in the human infant and is retained following perinatal brain damage.

**Neural Mechanisms and Gait Abnormalities in Children With Spastic-Type Cerebral Palsy**

One of the most controversial issues in human neurobiology today is whether the coordination of human locomotion is solely a function of spinal central pattern generation or whether higher brain centers are essential for the maturation of the human gait pattern.\textsuperscript{39,46,47} With respect to locomotion, central pattern generation refers to structures within the spinal cord that are capable of autonomously generating reciprocal, temporally coordinated locomotion.\textsuperscript{35} Cats with a total transection of the spinal cord are capable of overground and treadmill locomotion.\textsuperscript{27,32} The animals must be supported because they lack equilibrium responses, but appropriate reciprocal muscle activations and a full weight-bearing gait are apparent. Some mammalian locomotion, therefore, is possible without input from higher brain centers (eg, following transection of the spinal cord).\textsuperscript{46} Locomotion exhibited by animals that have had their spinal cords transected is, however, not purposeful locomotion. Rather, it resembles reflexive behavior.

The innate stepping movements of human fetuses\textsuperscript{48} and the bipedal ambulation exhibited from the day of birth by human infants, both typically developing\textsuperscript{49} and with anencephaly,\textsuperscript{50} support the existence of spinal cord locomotor-generating circuits in humans, at least early in ontogeny. Although autonomous spinal cord-mediated locomotion has been
demonstrated in many mammals and in simian infants, it has not been

demonstrated by fully mature simians, or humans.47 The stepping move-
ments of typically developing, nondisabled infants that are present at birth
become difficult to elicit between the second and eighth months of life. After
the eighth month, with the continued emergence of equilibrium responses,
locomotion reappears as a goal-directed behavior. Once goal-directed
ambulation emerges in typically developing children, it undergoes dramatic
changes over the next few months.51,52 This chronological progression of
human locomotion is very similar to the emergence of placing reactions in
cats. Both behaviors are present at birth, tend to disappear for a period of
time, and then reemerge to be used in more complex movements. There is
strong evidence that placing in cats is first mediated by segmental pathways
but then becomes dependent on the sensorimotor cortex during matura-
tion.19,41 Could a similar change in anatomical substrate underly human
locomotion?

To examine this question, a series of experiments were designed to study
the development of gait of children with mild to moderate spastic-type
cerebral palsy.39 Studies of individuals with a similar diagnosis have pro-
vided autopsy evidence58 and imaging technique data54,55 that indicate the
primary lesion in spastic-type hemi-plegic or diplegic cerebral palsy is in
the sensorimotor cortex, internal capsule, or pyramidal tract. Therefore,
it was possible to consider the influences of partial removal of supraspi-

Figure 2. Dark-field photomicro-
graphs of the thalamus following unilat-
eral sensorimotor cortex injections with
the neural tracer horseradish peroxidase/ 
(wheat germ agglutinin (HRP/WGA). (a)
One-day-old animal: Dense ipsilateral
labeling is seen throughout the dorsal
thalamus and extending into the contra-
lateral thalamus. (Magnification ×100.)
(b) Chronic neonatal operate: Ipsilateral
labeling following injections into right
undamaged sensorimotor cortex of adult
neonatal operates is similar to ipsilateral
labeling in a normal adult. In addition,
there is contralateral labeling in intralaminar and ventral nuclei. (Magnifi-
cation ×50.) (c) Normal adult animal:
Labeling is only found ipsilateral to the
sensorimotor cortex injections. (Magnifi-
cation ×50.) (Reprinted with permi-
tion.27)
nal input on the development of human locomotion. The experiments also provided the opportunity to discern possible etiological factors underlying the gait disorders associated with spastic-type cerebral palsy.

The first set of experiments involved surface electromyographic (EMG) recordings and kinematic analyses of six lower-extremity muscles.39 The lower-extremity locomotor patterns of infants with cerebral palsy of mild to moderate involvement and of typically developing, nondisabled infants were indistinguishable from each other during early walking responses.39,49 Stepping for both groups included synchronous joint movements, excessive muscular co-contraction, and short-latency EMG spiking (bursts of very short duration) of numerous muscles, especially during the foot-contact phase of the step cycle (Figs. 3, 4). Differences emerged when the children began the transition from supported to independent, goal-directed locomotion. During this period, nondisabled children very quickly developed reciprocal muscle activity, decreased muscle contraction durations, and asynchronous joint movements. In contrast, children with cerebral palsy retained many of the characteristics of the infant locomotor pattern. Most notable and invariable were excessive muscular co-contractions during movement and the continued existence of short-latency reflex spikes. Similar findings have been reported in a study of older individuals with cerebral palsy.56

The lack of transformation to a normal, mature gait in children with cerebral palsy suggests that the sensorimotor cortex and its projections are involved in the development of a normal gait pattern. Central pattern generators, although they certainly contributed, in part, to a lack of development of descending corticofugal projections and the repercussions of this failed development. The repercussions of damaging cortical projections perinatally may include interneuronal disruptions. In rats and cats, there are considerable competitive interactions for synaptic sites between spinal segmental projections and descending supraspinal systems during development.45,57 Spinal neural mechanisms (eg, interneuronal and presynaptic connectivity) may be affected in humans after perinatal brain damage.

**Hyperreflexia**

Individuals with spastic-type cerebral palsy have accentuated myotatic reflexes. They also exhibit reflex irradiation. Following a tendon tap to a single muscle group (eg, quadriceps femoris), EMG potentiations can be recorded from the stimulated muscle, its antagonist (ie, hamstring muscles),9 and other muscles distant to the site of stimulation.10 Reflex irradiation is also observed in typically developing, nondisabled infants.10,58,59 Reflex irradiation can result from loss of descending inhibition from higher centers or from la fiber excitation.10 If, similar to the results of nonhuman animal studies, la fiber projections exhibit excitation during perinatal development, then lesions to the descending systems during this time partially remove competitive interactions and may result in a retention of neural excitation. This abnormal retention could result in the irradiation of reflex responses. Myotatic reflex irradiation in nondisabled infants and in individuals with spastic-type cerebral palsy provides indirect evidence of neonatal neural excitation and its retention following perinatal brain damage in humans. Further insights will be possible by examining the myotatic reflex responses of subjects following adult-onset cerebrovascular accidents (CVAs). These studies are currently in progress (Leonard et al, unpublished results).

The gait of individuals with cerebral palsy59,60 is considerably different from that of individuals whose sensorimotor cortex was damaged as adults.15,60 Nonhuman animal data indicate that dissimilar neuronal mechanisms underlie the motor deficits seen following perinatal and adult-onset brain damage.22,33 The human response to brain damage probably also depends on the stage of development of both damaged and surviving pathways at the time damage occurs. Partially damaged pathways may sprout,51,62 whereas undamaged pathways may retain projections normally lost during development if damage occurs prior to a critical period.22 The neural substrate subserving hyperreflexia and spasticity in individuals with cerebral palsy and those with adult-onset CVA is, therefore, likely to be quite different.

**Neural Mechanisms Subserving Spasticity and Abnormal Muscular Co-contraction Activity During Voluntary Movement Following Perinatal Brain Damage**

Abnormalities in muscle tone at rest, during passive movements, and during active voluntary movements are common clinical features of the person with spastic involvement. Controversy exists regarding the pathophysiology underlying spasticity. Deficits in the neural mechanisms subserving reciprocal inhibition may be involved in spasticity and also in the excessive muscular co-contraction associated with voluntary movement in the person with spasticity. Reciprocal inhibition is one mechanism by which an antagonist muscle is inhibited during an agonist contraction. This inhibition can be detected with H-reflex testing. H-reflex testing provides an indirect measure of the excitability levels of alpha motoneurons.93,94 A large H-reflex amplitude indicates increased excitation of alpha motoneurons, whereas a small H-reflex indicates less excitation. The methodology and necessary controls for H-reflex testing are fairly complex. Basically, they involve electrically stimulating a peripheral nerve and recording, via a surface or indwelling electrode, the EMG potentiation of the muscle innervated by the stimulated nerve. The reader is referred to Schieppati94 and Leonard and

70 / 758

Physical Therapy / Volume 74, Number 8/August 1994
Figure 3. Rectified and filtered electromyographic recordings of five leg muscles of (A) four neurologically intact children and (B) four children with cerebral palsy during supported and independent treadmill walking. Recordings of muscle activity from five representative step cycles were normalized and superimposed. Onset of foot contact is marked by dotted vertical line at left. Step cycle is divided into stance phase (solid bar) and swing phase (dotted bar). LG=lateral gastrocnemius muscle, TA=tibialis anterior muscle, HAM=biceps femoris muscle, RF=rectus femoris muscle, GM=gluteus maximus muscle. (Reprinted with permission.39)
Individuals with cerebral palsy are unable to perform smooth coordinated movements, but rather, when initiating or executing movement, exhibit agonist/antagonist co-contractions. H-reflex testing procedures revealed that gastrocnemius-soleus muscle alpha motoneurons were not inhibited during voluntary dorsiflexions of the foot. Amplitudes increased during dorsiflexions (Fig. 5B). Unlike the reflex activity of nondisabled subjects, there was no decrease in the gastrocnemius-soleus muscle H-reflex prior to tibialis anterior muscle activation (Fig. 6B). Individuals with cerebral palsy clearly exhibited a deficit in the supraspinal component of reciprocal inhibition. The possibility cannot be excluded, however, that spinal mechanisms were also impaired. Changes in the H-reflex prior to movement are conveyed from supraspinal centers via spinal interneurons. Alterations of interneuronal circuits may obstruct transmission from supraspinal centers. The lack of inhibition of the gastrocnemius-soleus muscle H-reflex during tibialis anterior muscle contraction, when Ia afferents normally contribute to the inhibition, might also reflect damage to spinal circuits. Alterations in spinal structures following perinatal brain damage would not be unexpected because non-human animal studies have shown changes in spinal structures and in neurotransmitter development following perinatal brain damage.

Spinal mechanisms that contribute to reciprocal inhibition include Ia inhibitory interneuron-mediated inhibition, Renshaw cell inhibition, Ib fiber-mediated inhibition, and presynaptic inhibition of Ia afferents. Studies from two separate laboratories have thus far not shown deficits in Ia inhibitory interneuron-mediated inhibition in individuals with spastic-type cerebral palsy. Much work remains, however, before it can be concluded that spinal mechanisms are unaffected in individuals with cerebral palsy. The same methods that are used to assess the neural mechanisms underlying the spastic condition following perinatal brain damage can also be used to examine individuals with adult-onset brain damage and other diagnostic conditions.

Figure 4. Changes in temporal sequencing of joint movements during transitions between flexion (○) and extension (●) before and after toe-off (vertical line) for neurologically intact children and children with cerebral palsy. For comparison, temporal sequences during infant stepping and adult locomotion are also shown. Foot contact (FC) is represented as a vertical dotted line. Circles are means of latency of flexion/extension direction changes in hip (H), knee (K), and ankle (A) derived from eight step cycles per child. (Reprinted with permission.)

Moritani for a more thorough description of H-reflex methodologies.

During a voluntary tibialis anterior muscle contraction and subsequent dorsiflexion of the foot, there is a decrease in the gastrocnemius-soleus muscle H-reflex in nondisabled individuals (Fig. 5A). The inhibition occurs prior to agonist contraction (Fig. 6A). Because the inhibition of an antagonist occurs prior to this muscle receiving any afferent information from the contracting agonist, the inhibition must be mediated by supraspinal pathways. Reciprocal inhibition, therefore, although mediated via spinal interneurons, is not purely a spinal reflex but, in humans, involves supraspinal centers as well. Therefore predicted that individuals with upper motoneuron lesions would exhibit deficits in reciprocal inhibition. Experiments of individuals with cerebral palsy were designed to test this hypothesis.
Figure 5. Representation of one 2-second trial during H-reflex testing of the gastrocnemius-soleus muscles during voluntary dorsiflexion by (A) a 16-year-old neurologically intact boy and (B) a 14-year-old boy with spastic-type diplegia. Ten stimulations are displayed behind each other in successive order, with time scale for onset of stimulations on left. During the 2-second trial, the standing subject was asked to dorsiflex, as shown by electromyographic (EMG) signal of tibialis anterior muscle on right of graph. H-wave decreased from 3.96 to 0.96 mV, 48 milliseconds before onset of tibialis anterior muscle EMG activity in the neurologically intact boy, but H-wave amplitudes increased following onset of tibialis anterior muscle activation in the boy with cerebral palsy. A=stimulus artifact, M=M-wave, H=H-wave, TA=tibialis anterior muscle raw EMG signal. (Reprinted with permission.)

Implications for Therapeutic Intervention

Perinatal Versus Adult-Onset Brain Damage

It is becoming increasingly clear that the neural consequences resulting from brain injury differ depending on the age of the individual and the stage of neural pathway development at the time of injury. Because a child's nervous system is at such a dynamic period of change, the consequences of damage to the system will vary considerably, dependent on the age of the child at the time the damage occurs as well as the location, extent, and type of damage. Differing neural mechanisms appear to subserve the movement dysfunctions associated with perinatal or adult-onset brain damage. Initially, problems may be solely attributable to the CNS damage. Central nervous system abnormalities, however, also produce peripheral abnormalities. Secondary abnormalities of muscle, tendon, and bone, in addition to neural changes located away from the original damage, may increasingly contribute to the disability. All of these factors may contribute to motor control difficulties encountered following perinatal brain damage. The predominant role of each factor may be different at different stages of development. Studies are currently in progress to develop clinical testing procedures for determining the relative influences of neural and nonneural components on disability. Clinical tests are also being developed by a number of laboratories that will help to determine the various neural mechanisms underlying spasticity.

The spasticity that is seen in an individual with cerebral palsy, although clinically similar to that associated with adult-onset brain damage, probably has a different neural substrate. The spasticity associated with spinal cord lesions, multiple sclerosis, cerebral palsy, and adult-onset CVA responds differently to different medications. The fact that the spasticity associated with various neurological disorders responds differently to different medications is evidence that spasticity is not a singular entity. If the underlying causes of spasticity vary, then the physical therapy techniques used should likely differ among patient populations. This is assuming that physical therapy procedures can be shown to have specific and lasting effects.
effects. This has yet to be adequately demonstrated.72-74

Early Intervention

Many neural and nonneural organizational changes that occur in humans take place fetally. These and numerous other subsequent developmental changes are genetically determined.17,19 These changes, therefore, are unalterable by physical therapies. Synapse formation, dendritic sprouting, and refinement of neural pathways, however, continue throughout adolescence and beyond.

The cerebral cortex in particular exhibits considerable plasticity, especially during early neonatal development.19,22,75 Both nonhuman and human data indicate the brain's structure is affected by activity. The horizontal laminations of the cerebral cortex appear to be genetically predetermined,19 but vertical columnar organization is dependent on functional activity.10,19,26 Vertical columns in the cerebral cortex are composed of neurons that form functional units (e.g., various sensory input such as pressure, stretching, pain, and so forth from a finger will converge on one vertical column). These columns expand or shrink, dependent on the amount of activity these columns receive. Use of a particular neural pathway enhances neurotransmission along the pathway.29,76 These data suggest the importance of functional activity in neural remodeling and neurotransmission. The plasticity data, together with data demonstrating the effects of activity on neural remodeling, provide a strong theoretical basis for early intervention.

Visual system research, with nonhuman animals, has shown that development of the visual cortex depends on normal visual experience.23,77 Other vertebrate studies have shown modifications of CNS connectivity that are dependent on functional activity.22,30 Rats, raised in an enriched environment that required motor skill acquisition, exhibited expansion of the motor areas of the cerebral cortex.30 Similarly, it has been shown that hu-
The executive summary of a consensus conference that sought to examine the efficacy of physical therapy in the management of cerebral palsy stated that "no definitive support for the efficacy of physical therapy, or lack thereof, in the management of CP [cerebral palsy] exists in the research literature."74 Validating the effectiveness of early intervention in humans by precise, controlled experimentation may prove to be an evasive problem because of the inability to adequately control extraneous variables and because of ethical, legal, and moral issues. For these reasons, it is necessary to look, in part, to nonhuman animal research for data concerning early intervention. Nonhuman animal research unequivocally indicates the potential benefits of early experience on neural and nonneural development.9 The challenge to therapists remains to find the best means to effectuate change.

**Suggested Treatment Guidelines**

**Spasticity**

Spasticity is a common feature following certain types of perinatal or adult-onset brain damage. The neural substrate subserving the disorder appears to vary, dependent on diagnosis and the age of onset of injury. Accentuated alpha motoneuron discharge is present regardless of the age of onset of damage.82 Other neurophysiological variables, however, seem to show age-related differences. Reflex irradiation is present in individuals with cerebral palsy,9,19 but does not appear to be present following adult-onset CVA.9

Additional factors to be considered are nonneural influences. Resistance to passive stretching may be due to musculotendinous as well as neural factors.83,85 Length/tension curves plot the amount of tension that results from progressive passive lengthening of a muscle. Restriction caused by connective tissues, and not reflex activity, causes a sharp increase in the slope of length/tension curves when muscle fibers are stretched beyond 150% of resting length.83 Children with spastic-type cerebral palsy have muscle shortening and decreased passive compliance (elasticity) of the triceps surae muscles.84,86 With both neural and nonneural influences in mind, there appear to be several physical therapy procedures that appear to decrease spasticity or that might address age-related differences in the condition.

Prolonged stretching decreases muscle responsiveness to elongation induced during the first few degrees of movement and decreases alpha motoneuron activity.87 Immobilization in lengthened positions over time increases sarcomere numbers and results in an increase in muscle length.88 Techniques that use prolonged stretching to decrease spasticity, such as inhibitive casting and deep tendon pressure, therefore, appear to be scientifically valid. Immobilizing the triceps surae muscles of children with spastic-type cerebral palsy in a lengthened position for 3 weeks increased muscle passive compliance.86 Air splints89 and tendon pressure90 have been shown to decrease alpha motoneuron excitability in patients with adult-onset CVAs. All of these effects, however, are short-lived and last only as long as the application of the splints or tendon pressure.86,89,90

Hyperactive stretch-induced reflexes appear to have a more deleterious effect on ambulation in individuals with cerebral palsy than in those with an adult-onset CVA.96,99 Therefore, use of inhibitive casting, splinting, and deep pressure may lead to more functional changes in a younger population. It has been reported, however, that a single treatment session consisting of 30 minutes of a prolonged stretch to the gastrocnemius-soleus muscles did not improve the gait of subjects with cerebral palsy.92 Additional work examining other protocols appears to be indicated. Techniques that have a long-lasting effect are needed.

Biofeedback appears to have great promise in helping to reduce the detrimental effects of spasticity during voluntary movements performed in a controlled setting. Monkeys have learned to decrease alpha motoneu-
ron excitability through biofeedback.95 Because humans have greater cortical input onto alpha motoneurons than do monkeys or any other species,94 there is no reason to believe that humans cannot achieve the same level of control. Using biofeedback, individuals with cerebral palsy have gained the ability to control single motor units.95 Whether the ability to control alpha motoneuron excitability and other neural functions will lead to functional gains is yet to be determined. This will be an important determination as various functional activities require motor unit recruitment patterns that differ considerably from one another.

It is important to note that reduction of spasticity does not necessarily result in functional gains;96,97 There is a notable absence of controlled studies that indicate spasticity reduction improves motor behavior.96 Functional gains must be the goal of therapeutic intervention. Therapy, therefore, must address many other aspects of movement dysfunction in addition to spasticity reduction.

Techniques to Elicit Voluntary Movement

Antagonist muscles are inhibited prior to agonist activation during voluntary movements.8 Individuals with cerebral palsy have difficulty terminating muscle contraction and inhibiting antagonist muscle contractions during movement.8,95 Spasticity probably contributes to this movement disorder; but, as previously discussed, it also appears to reflect a problem in the integration of higher brain center projections with spinal cord circuitry.8 This integration is highly affected by experience and learning.22,28,39,98 Techniques that encourage and teach patients to inhibit antagonist muscular contraction during voluntary movement, therefore, appear to be appropriate.

Surface EMG biofeedback is a relatively easy way to provide a patient with ongoing information about agonist and antagonist muscle activity during a functional activity. A hyperactive triceps surae muscle that activates inappropriately during tasks that require ankle dorsiflexion is a common problem following upper motoneuron damage. This problem can be treated by providing the patient with feedback about the muscle's activity during a task. For instance, the patient can be instructed to maintain relative quiescence in the muscle during stance. Once this ability is mastered, the patient can be progressed to keeping the muscle silent during active ankle dorsiflexions and during the swing phase of gait. Modifications of this protocol have been used with some success.99

Because H-reflexes are better indicators of alpha motoneuron output than EMG activity, H-reflex biofeedback techniques may prove to be a more effective method for controlling spasticity and muscular co-contraction. Any biofeedback technique will be limited by the patient's age, cooperativeness, and cognitive functioning. It is also important to note that biofeedback training of one task may not carry over into another task100 and that not all patients will benefit equally from biofeedback training.101

Gait Training

Individuals with cerebral palsy often appear to develop aberrant ambulation patterns secondary to a lack of integration of supraspinal centers with segmental circuitry.59,102 Their ambulation patterns vary, dependent on the nature and extent of the CNS damage and subsequent musculotendinous changes. Common to all ambulation patterns are unique personalized characteristics that allow the attainment of the most energy-efficient gait available within the individual's window of adaptable change.103,104 This finding should be considered by therapists during treatment intervention. Working toward a "normal" gait pattern that is not efficient for a particular individual will probably decrease functional abilities.

One common gait abnormality, which perhaps reflects the lack of supraspinal and segmental integration, is the inappropriate timing of the gastrocnemius muscle during gait. Children with cerebral palsy frequently do not have adequate push-off to initiate swing but rather initiate the swing phase with hip flexion.59 The majority of children with cerebral palsy can adequately activate the gastrocnemius muscle.8,59 The problem is that the gastrocnemius-soleus muscles are not activated in the proper temporal sequence.59 Temporal sequencing of muscle activation involves spinal center pattern generators and integration of these neural circuits with input from higher brain centers.8,66,105 One approach that can be used to modify temporal sequencing problems, such as inappropriate activation of the gastrocnemius muscle, is treadmill walking. This type of training, in addition to altering the sequencing of muscle activation patterns, appears to encourage a functional, energy-efficient gait pattern in individuals with spasticity.106–108

Treadmill training, although slightly functionally different from overground locomotion training, provides a controlled environment that has several advantages. The patient's weight can be supported to compensate for deficits in balance and strength. Extraneous upper-extremity movements can be controlled, speed can be varied, and many repetitions are possible in a short period of time. The patient can be cued verbally or with biofeedback procedures. It is also possible to combine treadmill training with various functional electrical stimulation techniques. Treadmill training in conjunction with the use of cutaneous reflexes to enhance the locomotor pattern has been used successfully.108 Appropriate activation of the gastrocnemius-soleus muscles is not the only variable that can be addressed with treadmill locomotion. Treadmill training has been shown to change other gait variables of subjects with spasticity.106 Treadmill training combined with certain spasticity-reducing drugs appears to have considerable promise.107 Determining whether improved treadmill locomotion results in improved functional overground locomotion or in im-
provement in other functional tasks will have to be determined.

Of equal importance will be the determination as to whether treadmill training is effective for all types of gait disorders and diagnostic groups. Perhaps treadmill training will be more effective as an early intervention following perinatal brain damage because of the increased CNS plasticity available to the system at this time and the effects of activity on this plasticity. The mechanisms underlying the effects of treadmill training may also be different among patient populations. For instance, it may help modulate CPG functioning in individuals with cerebral palsy, but caloric expenditure and enhancement of motor skill acquisition through repetition may be more important variables following adult-onset CNS damage.

**Treatments Based on Normal Developmental Sequence**

Recovery from CNS insult does not necessarily follow a developmental sequence. Treatment techniques that advocate strict adherence to a normal developmental progression, therefore, need to be examined closely. If a child is prevented from ambulating because he or she has not mastered sitting equilibrium responses, that child will not have the opportunity to "feel" and learn the sensations associated with bipedal ambulation. The child probably will not develop upright equilibrium responses, motor planning skills, or upper- and lower-extremity movement patterns required for ambulation. As discussed previously, normal neural development is dependent on activity. Whether the practice of lower level skills has any carryover to the skills required for higher level functioning is also questionable.

Orthopedic consequences of limiting movement and upright postures also need to be considered. Movement affects the formation and shape of joints. Weight bearing and muscle activity increase bone mass, help to shape joints and bones, and deepen the acetabulum.

**Summary**

It is becoming increasingly apparent that the neural and nonneural mechanisms subserving spasticity and movement dysfunctions of the patient with neurological deficits vary, dependent on diagnosis, the type, extent, and location of damage, and the age of the onset of injury. Even individuals within a specific diagnostic grouping do not appear to share a singular underlying cause to their disability. Therapists, therefore, should not expect a singular treatment technique to be equally effective with all persons with neurological deficits. The treatment suggestions previously discussed are not all-inclusive but represent techniques that are compatible with current scientific knowledge. As our scientific base changes, it is expected that all treatment techniques will undergo modifications. Research that continues to integrate basic and clinical sciences should provide increasingly more effective, patient-specific treatment approaches.

**Acknowledgment**

I wish to express my appreciation to Dr Richard Gajdosik and Carol Gajdosik for their valuable reviews of this article.

**References**


25. Effner CD, Lunsden AGS, O'Leary DDM. Target control of collateral extension and di-
and Posture and Gait: Development Adaptation stretch on muscle activations during gait in a single session of prolonged plantar-flexor physical therapy.


Motor Behavior and Neural Changes Following Perinatal and Adult-Onset Brain Damage: Implications for Therapeutic Interventions
Charles T Leonard
PHYS THER. 1994; 74:753-767.