The Historical Development of Neuroscience in Physical Rehabilitation

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Neuroscience and occupational therapy in physical rehabilitation have developed along parallel tracks. As physicians began to study the neural bases of motor control, they also began to reconsider the sequelae of "hopeless" diagnoses as conditions that they could influence. This change in some physicians' understanding of the neural mechanisms of motor control influenced other clinicians' ideas about patient care. Early work on treatment of patients with cerebral palsy and polio led to improvements in treatment approaches used to facilitate motor skill and functional motor ability in patients with upper motor neuron disorders. From the 1950s to the present, therapists have refined their treatment techniques as knowledge from neuroscience has become available. A few therapists, who are gradually increasing in number, have turned to the laboratory to study basic neuroscience problems that affect clinical treatment. This article describes the development of neuroscience research and neurorehabilitation theories and indicates common themes.

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The translation of basic science information into treatment concepts is a key problem for applied disciplines such as occupational therapy. Occupational therapy culls concepts and information from many fields, including neuroscience. The history of neuroscience extends back to the beginnings of recorded history; the history of occupational therapy in physical rehabilitation is less extensive. Although these two fields differ in many ways, some similarities may be found. For example, both neuroscience and physical rehabilitation are characterized by several developmental periods that differ in time. Similarly, the practitioners in both fields have changed over time from self-taught generalists who worked by themselves and were supported mostly by private funds to university-trained specialists who work with other professionals and are supported by public as well as private funds.

Because of the inevitable time lag between the development of the basic science and its translation into clinical science, the incorporation of these new ideas about the nervous system into treatment theory has taken many years. Thus, the time frames of knowledge development in neuroscience and theory development in occupational therapy are not congruent. For example, occupational therapists began to treat patients with physical disabilities long after the first concepts in neuroscience were developed, at a time when many rehabilitation workers were beginning to translate new scientific concepts about the nervous system into treatment approaches.

Table 1 identifies some key issues and ideas that have evolved in neuroscience and that have correlates in physical rehabilitation, including occupational therapy. This article follows the ideas listed in Table 1 through their historical development. These ideas have influenced the development of treatment models for upper motor neuron disorders.

Assumptions

The remainder of this article is based on several assumptions:

1. The development of treatment theory and technique should be based on logical, objective reasoning grounded in empirically derived basic science.
2. In the basic sciences, at least three things happen over time: (a) the quantity of knowledge of natural phenomena increases, (b) insights into the meaning of those findings change our understanding of their importance, and (c) new understandings change the direction of the research.
3. The progress of science, viewed in the context of...
The ancient Egyptians understood that damage to the brain could impair behavior, but they did not consider the brain itself to be important. One thousand years later, the ancient Greeks thought that the brain contained the soul and that sensory and motor nerves originated there, but they did not realize that the brain could be studied empirically (Finger, 1994). Many generations later during the Renaissance, Leonardo da Vinci studied the brain. His notes indicate that he thought animal spirits resided in the ventricles (Clayton, 1992). Although da Vinci understood that the brain could be dissected and studied, his work was not published until centuries later, so his insights were not available to other investigators.

Two hundred years after da Vinci, Descartes reaffirmed the Greek notion that the brain contains the soul. Independently of da Vinci, Descartes introduced the radical idea that the brain and the body could be dissected and studied in parts. This idea opened the way toward anatomical and physiological studies of the nervous system (Corsi, 1991). Descartes was also one of the first investigators to describe automatic behaviors that we would now call reflexes, although he ascribed these behaviors to the actions of spirits. Around the same time, Willis published the first ideas about localization of function in the brain (Finger, 1994).

In the early 18th century, Pourfour du Petit performed the first experiments that showed that the nerves control motion, but he maintained that the nerves carried animal spirits. Later, in the mid-18th century, Whytt showed that only a small segment of spinal cord is necessary for a simple reflex (McHenry, 1969). In the 19th century, scientists accepted the idea that sensory and motor nerves were separate. This notion was followed by the first reports confirming the concept of localization of function by Broca, Jackson, Ferrier, and others (Finger, 1994).

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### Table 1

<table>
<thead>
<tr>
<th>Neuroscience</th>
<th>Rehabilitation</th>
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<tbody>
<tr>
<td>1. The brain can be studied empirically.</td>
<td>1. The patient can be treated.</td>
</tr>
<tr>
<td>2. The brain is a dynamic system.</td>
<td>2. The entire system of the person must be treated.</td>
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<tr>
<td>- The functions of the system cannot be described by only knowing the anatomy.</td>
<td>- Problems resulting from damage to one part of the system can be treated by trying to influence that part of the system or other parts.</td>
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<tr>
<td>- The functions in one area influence the functions in other areas.</td>
<td>- Patients have multiple problems from damage in one area.</td>
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<td>3. Sensation influences motion.</td>
<td>3. Sensory input can be given to influence motor output.</td>
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<td>4. The brain has some localization of function.</td>
<td>4. The units of movement can be manipulated during the therapy.</td>
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<tr>
<td>5. The brain has some equipotentiality.</td>
<td>5. Damage to some areas cause specific deficits.</td>
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<td>6. Movements are programmed and performed using smaller movement subunits.</td>
<td>6. Stimulation can influence recovery of some function.</td>
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<td>- To move, the system must control multiple and redundant degrees of freedom.</td>
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<td>- To solve the degrees of freedom problem and to simplify the processing of motor commands at higher levels, the system uses functional movement groupings at lower levels.</td>
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<td>7. Physiological processes underlie plasticity, that is, the brain can learn.</td>
<td>7. Patients with brain lesions can learn or relearn cognitive and motor behaviors. Therefore, neurorehabilitation techniques will influence the patient's behavior.</td>
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history, is a plodding process, sometimes taking lifetimes to progress and often occurring in fits and starts. With the luxury of hindsight, many ideas may seem obvious and unexciting, but when initially proposed, they were often considered heretical, such as the neuron theory of the brain discussed in the next section. Out of extreme ideas, however, important rational concepts developed on which much of the current research is based. This same kind of progression can occur with the development of applied concepts in medicine and rehabilitation.

4. As basic knowledge changes and evolves, so should the applications derived from that knowledge.

### Origins of Neuroscience and Physical Rehabilitation

Occupational therapy is founded on a single idea—occupation is essential to human life (Dunton, 1919). Neuroscience, too, is founded on a single idea—the brain can be studied and understood. This concept, which took centuries to develop, is the foundation of all neuroscience research and related clinical applications of that work. As neuroscience began to reveal brain functions and the role of external influences on brain function, new ideas provided the framework for clinical neurology, setting the stage for the development of intervention strategies. Some of the most notable intellectual advances in this progression of knowledge development are discussed as follows.

### Neuroscience

The ancient Egyptians understood that damage to the brain could impair behavior, but they did not consider the brain itself to be important. One thousand years later, the ancient Greeks thought that the brain contained the soul and that sensory and motor nerves originated there, but they did not realize that the brain could be studied empirically (Finger, 1994). Many generations later during the Renaissance, Leonardo da Vinci studied the brain. His notes indicate that he thought animal spirits resided in the ventricles (Clayton, 1992). Although da Vinci understood that the brain could be dissected and studied, his work was not published until centuries later, so his insights were not available to other investigators.

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Schwann, supported by the work of Purkinje and others, had suggested early in that period that the brain is made of individual cells or neurons (McHenry, 1969). Toward the end of the 19th century, with the development of improved technology such as microscopes and specialized staining techniques, natural scientists finally accepted the neuron theory of brain structure. The neuron theory, which is the basis for modern neuroscience, took more than 70 years to become accepted (Finger, 1994).

These advances facilitated essential work in neuroanatomy by the early (19th century) neuroanatomists, such as Nobel-prize winner Ramón y Cajal. Overlapping in time with Cajal's extraordinary work, more than a 50-year period from the late 19th century to the early 20th century, Sherrington (1947) studied the physiology of the nervous system and the relationships between sensation and motion, laying the groundwork for later research on motor control. Around the same time, a different group of investigators developed the ideas that eventually formed the bases for neuropsychology. They debated the problem of localization of function versus generalized functions, a problem that remains unresolved. In the early 20th century, Head developed the notion that the brain has many areas with localized functions, but a lesion of one area can affect the entire brain (Finger, 1994). He also developed the idea that after brain lesions occur, new schemata can be developed, an essential concept for neurological rehabilitation.

Early in the 20th century, Franz combined the ideas of localization and equipotentiality—the concept that any area of the brain can do anything. From his work came the understanding that the brain has some localization of function, but it is not strictly localized, and the brain may have some plasticity. Lashley then showed that all brains are not exactly alike, so localization is not absolute (Finger, 1994).

In summary, during the early development of neuroscience, investigators were natural historians who came from diverse backgrounds, including philosophy and theology as well as medicine. The direction of their research was solely driven by their own personal interests, and most investigators worked in relative isolation, funding their work from their personal resources. To develop those few, but important ideas, a smattering of isolated scientists worked over a period of several thousand years.

Physical Rehabilitation

The World War I era reconstruction aides, forerunners of physical and occupational therapists (Anderson, 1968), treated primarily orthopedic injuries because few patients with brain damage survived the war. Before and after the war, treatment teams were organized to treat patients with polio. The physical therapists on those teams used the muscle reeducation approach with polio victims (Pinkston, 1989). In those days, children born with cerebral palsy were kept at home. Those who could move well enough to care for themselves or help with chores were taught to do so, but attempts at influencing the nervous system were unusual. Similarly, those few persons who survived head injuries or other brain damage received humanitarian maintenance care, but systematic programs of rehabilitation were rare.

In the 1930s, however, a sea change occurred, starting with the work of Phelps (Jones, 1967; Phelps, 1941) who recognized that children with cerebral palsy could be trained and who believed that they should be trained. This understanding of the potential for change, similar to the understanding of the potential to understand the brain, is the basis for modern neurorehabilitation. Phelps recommended the self-care approach in which treatments were planned to follow a logical sequence, with treatment programs unique to each patient. In other words, he used a logical, objective, scientific method. Although we take these ideas for granted today, at the time, they were radical notions. Phelps prescribed passive, active assistive, and active motions, with the goal of independence in self-care. These new concepts of independence in self-care developed through active intervention remain important principles in neurorehabilitation, especially in occupational therapy. Although these concepts, and the ideas introduced by the next group of theorists, have been recycled and reintroduced in new forms, the basic underlying treatment principles originated with this work.

Notable events in society occurred around the time that Phelps developed his philosophy. Health care improved as World War II brought the development of antibiotics, improved techniques for reducing brain edema, and improved technology. Young men injured in the war were more likely to survive and needed rehabilitation, including occupational therapy. More persons who had strokes survived, and more persons began to live into old age. In this immediate postwar era, the major influence on physical rehabilitation came from the orthopedic models (Gutman, 1995; Pinkston, 1989) and later from the new work in developmental psychology by Gesell and others (Gesell & Amatruda, 1941).

Like the early neuroscientists, the early rehabilitation specialists came from diverse backgrounds. Physical therapists had backgrounds in massage therapy and physical education; occupational therapists had backgrounds in handicrafts and fine arts (Anderson, 1968). During this period, neuroscience had little or no influence on phys-
cal rehabilitation, including occupational therapy. In contrast to the development of neuroscience, however, neurorehabilitation took only 20 to 30 years to move on to the next phase of theory and practice development.

Developmental Periods

Neuroscience

In the mid-20th century, improvements in technology accompanied increased survival rates for patients with brain injuries, and the polio epidemic swept the country. These social factors provided the impetus for government support of research related to understanding and curing neurological disorders (National Institutes of Health, Division of Public Information, 1992). During this period, neuroscience diverged in several directions. Work on motor control continued, work on the neuropsychology of perception and cognition picked up speed, and work on cellular and subcellular anatomy and physiology increased. The prevailing models of the nervous system in controlling movement changed from the linear models to more flexible hierarchical models. Work on segmental reflexes and the underlying mechanism of the muscle spindle contributed to the understanding of the reflex as the basic unit of motion (Granit, 1955; Magnus & Rhines, 1948; Twitchell, 1954).

As neuroscientists embraced some ideas from systems theory (see Milsum, 1966), computational models became important in the theories about the neural control of movement (see Robinson, 1968). This use of more sophisticated models enabled movement scientists to consider the processes of the nervous system separately from the actual anatomy and in so doing, demonstrated that the functions of the system may be greater than the sum of its parts.

In the 1940s, the Russian physiologist Bernstein headed a group whose work arguably had the most notable impact on the direction of Western scientists' study of motor control since Sherrington's work because it presented a new frame of reference for understanding motor control. In his book, published posthumously in 1967, Bernstein proposed the systems theory of movement and posed all the major questions about motor control, which remain under investigation today, such as the degrees of freedom problem (see Appendix). By the end of this period of model development, the models of motor control, like those of the nervous system, had evolved from simple linear models to complex hierarchical models in which the motor commands are given at higher levels of the nervous system, implemented by lower levels of the nervous system, and tuned locally as needed to interact with the environment (Greene, 1971; Whiting, 1984).

Bernstein's (1967) computational, or engineering, approach to building a theoretical, mathematical model of the nervous system enhanced research on motor control because it provided a theoretical framework, or yardstick, against which to test hypotheses. Bernstein's mathematical model was hierarchical in that it assumed a high-level control center and several lower levels that explained the details of movement, but the model was not rigid. Information could flow from either the lower levels up or the higher levels down. Furthermore, the model included several radical changes, as compared with previous models, in that it accounted for the influence of the environment on the performer and his or her unique biomechanics, and it considered multiple linkages among neural and biomechanical synergies.

Physical Rehabilitation

In the 1950s, several therapists-scientists developed the first neurorehabilitation treatment theories. Kabat, a physician, and Knott, a physical therapist, emphasized the patient's active participation and treatment in a developmental frame of reference. Her sensorimotor approach introduced the importance of neuromuscular mechanisms, with the reflex as the basic unit of movement, the use of the mass action patterns that Brunnstrom (1970) would later call synergies, and the importance of positioning. Kabat, Knott, and Voss also emphasized the use of both diagonal pattern motion and repetitive motion (Kabat, 1947).

In the mid-1950s, Rood's ideas about children with cerebral palsy began to have an impact on clinical treatment (Rood, 1952a, 1952b, 1954, 1964). Rood (who had dual training in occupational therapy and physical therapy), like Kabat and Knott, supported the use of a developmental frame of reference. Her sensorimotor approach emphasized the intimate relationship between sensation and motion and the use of sensory input to stimulate normal movement. She did not discuss central nervous system processing mechanisms but assumed a direct relationship between sensation and motion (Rood, 1964). Rood (1964) also emphasized the different, but related, roles of trunk movements for stability and limb movements for mobility. This idea preceded the English publication of Bernstein's (1967) book and his discussion of the degrees of freedom problem. The treatment techniques Rood taught involved moving through several stages of motor development combining trunk stability
and limb mobility. Rood's ideas were based on neuroscience research on sensory input to muscle spindles. So influential were her ideas that neuroscience education in the allied health disciplines emphasized the anatomy of muscle spindles and the use of proprioception and joint compression as movement-stimulation techniques. Unlike Kabat, Rood did not emphasize diagonal motions. She discussed using combinations of reflexes, although not in the same patterns discussed by Kabat, Knott, and Voss.

Shortly after Rood's work came to prominence, Brunnstrom's ideas on the treatment of patients with stroke became prominent in physical rehabilitation. Her stages of recovery approach were recycled ideas of reflexes and mass action patterns, but she called them abnormal synergies (Brunnstrom, 1970). Brunnstrom, like earlier theorists, thought that treatment for patients with stroke should follow a logical sequence. Unlike earlier theorists, however, she believed in following the usual sequence of recovery that such patients demonstrate, from flaccid extremities, to the dominance of abnormal flexion and extension synergies, ending in the redevelopment of controlled, isolated movements. She believed that facilitation of abnormal synergies would help patients move to the next level of recovery. Brunnstrom's system of abnormal motor patterns, as described in her book, is used by some therapists today. Although her treatment system has recently been reinterpreted in light of later hierarchical models and motor learning theories, it remains an essentially hierarchical model of treatment (Sawner & LaVigne, 1992).

Toward the end of this postwar period, in the 1960s, Bobath and Bobath became influential in the treatment of cerebral palsy and later with stroke. Their neurodevelopmental therapy approach emphasized the reflex as the major element of movement and position as influencing motor output. In particular, they focused on inhibiting abnormal movements, which they associated with primitive reflexes, and facilitating normal movements, which they associated with righting and equilibrium reactions. Unlike Brunnstrom, they believed in encouraging normal movement patterns and discouraging abnormal motions. Like Rood, they believed in emphasizing axial (trunk) motor development for motor stability before emphasizing limb motor development for mobility in a developmental sequence. They also considered abnormal muscle tone to be a major problem. Therefore, much of their early work discusses normalization of tone as well as normalization of reflexes (e.g., B. Bobath, 1948, K. Bobath, 1966). Thus, Bobath and Bobath reinterpreted many of the existing ideas about the importance of reflexes, tone, and abnormal movements in a new manner, and their fresh interpretation influenced practice. For example, their emphasis on reflexes led to the practice of evaluating the so-called "primitive reflexes"—stereotyped patterns of movements observed in infants, such as the asymmetric tonic neck reflex. Fiorentino's (1963) work on reflexes stems directly from this idea.

In the early 1970s, Ayres's (1972) book on sensory integration therapy reintroduced the notions that behavioral problems may have their roots in the central nervous system and that children with mild motor deficits should receive treatment. This approach drew on several concepts from neuroscience, such as the notion that behavior is generated by the nervous system and the notion of a relationship between sensation and motion. Her approach also drew on concepts from earlier work in physical rehabilitation by Phelps and by Rood—therapeutic intervention can alter motor behavior toward more normal expression. Even more than previous rehabilitation theorists, Ayres emphasized the interaction between the patient and the environment. This notion built on the older ideas about the relationship between sensory input and motor output but extended the context. It was also based on ideas outside neuroscience from the earliest phase of occupational therapy development in the arts-and-crafts movement, namely that the structure of the environment affects behavior and that changing the environment leads to changes in behavior (Hall, 1905, 1910).

Contemporary Period

Neuroscience

Modern neuroscientists have diverse backgrounds, allowing them to draw on a wide range of skills and academic disciplines, such as engineering, medicine, occupational therapy, physical therapy, and psychology. Neuroscientists with backgrounds in the allied health professions have followed this trend of diversity, pursuing a variety of academic disciplines in their doctoral, postdoctoral, and more advanced work. For example, occupational and physical therapists have pursued work in cellular physiology (e.g., Mun-Bryce, Kroh, White, & Rosenberg, 1993), sensory physiology and pharmacology (e.g., Carvell, Simons, Lichtenstein, & Bryant, 1991; Cohen, Cohen, Raphan, & Waepe, 1992; Jacobs & Juliano, 1995), motor control (e.g., Chan, 1988; Horak, Nashner, & Diener, 1992; Iyer, Christakos, & Ghex, 1994; Trombly, 1993), and neural mechanisms of plasticity and recovery after damage (e.g., Held, 1993). Neuroscientists now understand that the

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brain has multiple and movable centers of control, some of which largely function independently of the others but are affected by them, as is the case with autonomic nervous system centers. Neuroscientists today use a conceptual model of the nervous system as a complex, interrelated set of structures and functions and understand that the center of control in the motor system changes depending on the needs of the person as well as the constraints of the task and the environment existing at the time.

Physical Rehabilitation

Current work in neurorehabilitation is identified less with specific theorists and more with ideas taken from motor control research. Several therapists—scientists, such as those mentioned previously, are studying specific issues in the neural control of sensation and movement. Recently, some of this work has been applied to clinical problems (Cohen, Kane-Wineland, Miller, & Hatfield, 1995; Fetter, 1991; Sabari, 1991) in vestibular rehabilitation, motor development, and motor control. Horak (1991) has put the theoretical work on motor control from the past half century in an historical perspective. Additionally, Heriza (1991) and Held (1995) have summarized and updated the related practice models that parallel the linear and hierarchical motor control models. These latest hierarchical practice models start to bridge the gap between treatment techniques and motor control theory. The current treatment approaches are based on models of the motor system that are less rigidly hierarchical but, instead, have movable loci of control. In these models, the control center is determined by the immediate task demands and change. These models pose a conceptual difficulty for practitioners because they require both a broader perspective of the patient as part of a system and a more focused perspective to deal with the details of cognition, sensory processing, and motor control. In time, with continued research on the neural mechanisms of cognition and sensory and motor processes, the newer ideas about neural control of sensation and movement will be translated more fully into practice approaches.

The development of treatment theories continues. A time lag invariably occurs between the development of the basic science and the application of the new knowledge gleaned from that work. Therefore, the paucity of theoretical papers applying that knowledge to practice is not surprising. For that reason, practitioners' continued reliance on the older hierarchical models will take some time to change.

Current practice models based on recent motor learning and motor control research are returning to some concepts developed many years ago in occupational therapy. For example, Bernstein (1967) wrote in the 1940s that normal movement is goal directed, an idea that is remarkably similar to a basic tenet of modern occupational therapy that treatment activities should be goal directed or purposive (McNary, 1947). Bernstein also wrote that the major problem the motor system must solve in order to move is the reduction of the number of degrees of freedom used. His approach to systems theory and his model of motor control included the notion that the person must interact with the environment. Similarly, Held's (1993) work on recovery of function after brain damage suggested that stimulation from the interaction between the person and the environment is crucial. These modern ideas hark back to the origins of occupational therapy when the founders thought that the dynamic interaction between the environment and the person was important in controlling behavior (Hall, 1905) and that therapy should facilitate performance of purposeful activity (see Reed & Sanderson, 1992). In adopting the modern concepts of systems theory as they are now being applied to therapy, occupational therapists are not only rediscovering ideas on which the profession is based, but also are reinterpreting these ideas and applying them in new ways (Reed, 1986).

Summary

Traditionally, scientists have developed new knowledge in biology with research. Then, these ideas have been tested with clinical populations, and theorists and practitioners have applied them—a process that takes many years. This same process continues to occur today but with a new wrinkle because occupational therapy and the other rehabilitation specialties have produced neuroscientists who understand the ideas and problems in both areas. Because neuroscience findings can have major implications for treatment approaches, the rapid incorporation of these ideas into occupational therapy theory and practice is important, and the facilitation of this translation by occupational therapists who are well-versed in these ideas will aid the development of the profession. As Horak (1991) has pointed out, however, the time lag between new discoveries in neuroscience and their application in the clinic is long. Increasing our awareness of the relationship between neuroscience and the development of treatment theories should reduce this time lag and improve our ability to incorporate new knowledge into occupational therapy theory and practice, enabling us to facilitate improvements in patient care.
Appendix

Acknowledgment

This work was supported by the Clayron Foundation for Research.

The Degrees of Freedom Problem

Roughly stated, the motor system has multiple and redundant degrees of freedom (i.e., number of joints or degrees of range of motion) so that any motor task can be performed in several ways. For example, to reach for a coffee cup, one could flex and internally rotate the shoulder, extend the elbow, pronate the forearm, and flex the wrist. Alternatively, one could flex and externally rotate the shoulder, flex the elbow slightly, supinate the forearm, and extend the wrist. (This limited discussion, of course, completely ignores all the necessary activity proximal or caudal to the shoulder.) Somewhat, the motor system selects an efficient solution to the degrees of freedom problem for one to solve the motor problem of picking up the cup. Bernstein (1967) asked how the motor system solves that problem.

The degrees of freedom problem is relevant to therapists because patients are often unable to solve the problem, or they select inefficient solutions. For example, a patient with ataxia may be unable to control multiple degrees of freedom and thus may be unable to perform tasks requiring object manipulation. The therapist must assist the patient in discovering strategies for solving the problem. Similarly, an elderly person with a balance disorder may be able to solve the degrees of freedom when seated but is unable to solve the greater number of degrees of freedom when standing, selects a maladaptive strategy to solve the problem, and falls. The therapist must assist the patient in discovering new solutions to the degrees of freedom problem because previously learned solutions no longer suffice.

References


