Impact of Peripheral Nerve Injury on Sensorimotor Control

Susan V. Duff, EdD, OTR/L, PT, CHT
Pennsylvania State University
University Park, Pennsylvania

ABSTRACT: Deficits in sensorimotor control are experienced immediately after nerve injury due to changes in the periphery and central nervous system. Muscle denervation and sensory loss often disrupt prehensile coordination requiring the use of alternative strategies. To effectively foster coordination postinjury clinicians should address not only impairments and function but motor control issues through the prescription of specific sensory and motor experiences. Engagement in carefully planned, therapeutic activity can take advantage of the nervous systems' ability to regenerate and reorganize following nerve lesions. This article reviews motor control issues and neural reorganization concepts that may influence the recovery of skilled prehension following upper limb nerve injury. It also provides clinical guidelines for examining and enhancing coordination.

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Skilled prehension is the efficient and adaptive use of the hands and upper limbs to perform different tasks in various environments. Fine dexterity, an important aspect of prehension, is often taken for granted until it is lost or diminished, as when one sustains a nerve injury. Peripheral nerve injuries (PNIs) reduce muscular recruitment and sensation and can disrupt *coordination* through the changes that occur both in the periphery and the central nervous system (CNS).[1,2] Clinicians can affect the reorganization process to help individuals optimize sensorimotor control or coordination after an injury, through the prescription of specific sensory and motor experiences.[3–5] This article will 1) review components of prehension and relevant motor control concepts, 2) discuss neural reorganization and the affect of PNI on prehensile coordination, 3) provide alternative ways to assess motor strategies/learning, and 4) suggest methods to enhance sensorimotor control for use in prehensile tasks.

COMPONENTS OF PREHENSION

Prehension is the effective use of the hands and upper limbs as we reach, grasp, manipulate, and release objects.[6–8] Typically, we use vision to locate objects or targets in the environment. Although we can successfully interact with objects without vision, accuracy and precision are enhanced when it is used. *Reaching* involves transporting the hand to various regions of the workspace using adequate trunk stabilization or degrees of motion. *Grasp* incorporates various grip patterns to obtain and stabilize objects at opposing grasp points. *Manipulation* is the handling and movement of objects with one or both hands, sufficiently scaling the forces at contact and throughout. *Release* is the process of letting go or taking force off objects, as when playing the piano. Although some prehensile tasks can be performed with one hand, others demand bimanual coordination or coupling of the limbs.

MOTOR CONTROL CONCEPTS

The field of motor control examines how movement is regulated.[9] A few motor control concepts that are relevant to skilled prehension include 1) the management of redundancy, 2) the role of sensory information in anticipatory and feedback control, 3) motor lateralization/handedness, and 4) minimizing cost/optimization.[10,11]

Managing Redundancy

Bernstein[12] proposed that a primary role of the CNS is to manage the multiple degrees of freedom inherent in the neuromotor system. Degrees of

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Correspondence and reprint requests to Susan V. Duff, EdD, OTR/L, PT, CHT, 266 Recreation Hall, University Park, PA 16801; e-mail: <sue@wepi.us>.

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freedom are the number of independent elements available to perform a motor task, such as joint motion, muscles, motor units, or neural ensembles. *Redundancy* in the neuromotor system refers to the surplus of elements available to perform certain movements. Because of this redundancy, the degrees of freedom must be managed to allow for smooth coordination.

Early in skill learning we typically coactivate muscles to stiffen our joints perhaps in an attempt to minimize the degrees of freedom.[13,14] With practice and learning, we become more adaptive and are able to take advantage of the multiple degrees of freedom to make smoother and more efficient movements viewed together as *coordinative structures* or *synergies.*[15] The notion of movement synergy can be exemplified through the use of writing utensils during development. During early writing and drawing experiences, most children do not use a consistent pencil grip or pencil angle.[16] Yet, based on clinical experience, the pattern and angle frequently used by young children often incorporates more proximal than distal joint motion. With development and practice, pencil grips and angle patterns become less variable and more synergistic. Thus, older children typically employ more distal than proximal joint motion as shown with the dynamic tripod grip.[17] Research indicates that task complexity, individual characteristics, and environmental conditions influence the movement synergy used, and therefore should be taken into consideration during rehabilitation after PNI.[18,19]

Role of Sensory Information in Feedback and Anticipatory Control

Prehension makes use of current and previous somatosensory (tactile and proprioceptive), and visual information via feedback and anticipatory or feedforward control. *Feedback* is the sensory input received during movement. We use "on-line" feedback to make corrections during movement. We use previous feedback to adapt our responses to errors or unexpected events on subsequent attempts. For example, when we reach to grasp a glass we often preshape the hand before contact to a width or aperture wide enough to accommodate its size or shape.[7] In addition, at object contact we typically use opposing thus stable grasp points, ensuring balance.[6] Typically, we widen the aperture slightly larger than the size of the object, and then narrow it until contact is made. Thus, grip aperture is usually smaller when we grasp a potato chip and larger when we grasp a glass of water. However, if the grip aperture is not scaled appropriately, the grasp points will not be stable and the object will slip. Somatosensory feedback received from errors may be used to correct movements on subsequent attempts. Therefore, if a narrow aperture resulted in slippage, a wider aperture may be used on next effort. This advanced planning of movement based on previous sensory input, as when preshaping the hand (Figure 1), is termed *anticipatory control.*

We also use on-line feedback in conjunction with anticipatory control to regulate fingertip forces when grasping and manipulating objects. Previous sensory input gained from prior experience and current visual input, are used to plan the grip and load forces before lifts.[20,21] Just before objects are contacted and lifted, we grade or scale the amount of grip (normal or squeeze) and load (tangential or lift) force used to secure them in anticipation of expected texture and weight.[8] The grip and load force are usually increased in parallel, termed the *grip-lift synergy.* Typically a *safety margin* for slip is maintained, defined as the difference between the grip:load force ratio and the slip ratio (inverse of coefficient of friction).[21] In response to a slip, relayed by tactile cues, we usually increase the grip force on-line without letting go of the object. On the next object lift, we would probably use anticipatory control to maintain just enough grip force to prevent slippage.

As we manipulate objects we rely on tactile and proprioceptive cues to relay information such as contact and to trigger shifts from one phase of the grip-lift task to the next. These sequential phases include finger contact, preload, loading, static phase, replacement, unloading, and fingers off (Figure 2).[2] *Finger contact* is the phase in which we receive tactile cues that the object has been touched. In response, we

FIGURE 1. *Example of 5-month-old infant displaying anticipatory control by preshaping the hand to accommodate the size and shape of the rattle in advance of contact. (Courtesy of Shriners Hospitals for Children, Philadelphia, PA.)*

GRASP[Contact→Preload→Loading→Transition→Static→Replacement→Unloading→Fingers Off]**LET-GO**

FIGURE 2. Sequential phases of the grip-lift task from finger contact to lift and final release of an object.

begin to increase the grip force termed the *preload* phase. Then we begin to generate a load or lift force initiating the *loading* phase. During the loading phase, the grip and load forces increase in parallel until the object leaves the support surface. The *transition* phase is when the load force overcomes the object's weight and it leaves the surface. The period when the object is being held in the air is termed the *static phase*. The *replacement* phase begins when the object is returned to its support surface. In preparation for object release the grip and load forces decrease synergistically termed the *unloading* phase. The final phase is when the fingers are removed from the object, termed *fingers off.* Tactile and proprioceptive cues received during the grip-lift task provide signals to the nervous system and trigger transitions through each phase of the sequence. Peripheral nerve injury disrupts feedback and anticipatory control used in this sequential process, significantly prolonging the phases and reducing the coordination.[21,22]

The rate used to increase the grip and load force are termed the *grip* and *load force rate*, respectively. Typically, we increase force at a higher rate for heavier objects like a glass of water and a lower rate for lighter objects such as a potato chip. The amplitude or height of the rate (derivative of the slope of the force increase) is one way to measure anticipatory force scaling. Figure 3 shows the relationships among grip force, load force, load force rate, position of the object, and acceleration during a lift of an object. As shown, the load force rate begins to increase before the object leaves the support surface (position). Because we do not get weight information until the object leaves its support this increase in rate indicates the force is being planned in advance.

Motor Lateralization /Handedness

Motor performance between the two upper limbs is not symmetric, as shown through speed and accuracy tests,[11,23,24] yet the nondominant limb is not just an inferior version of the dominant limb. Sainburg and colleagues[11,25–27] have introduced a hypothesis of *dynamic dominance* to explain the differences in motor control found between the dominant and nondominant hemisphere/limb systems during reaching. Reaching requires that the *trajectory* (speed, direction and curvature), limb posture, and final position be controlled. Although each limb utilizes all features of control, based on their research examining planar reaching tasks, Sainburg and colleagues provide evidence that the dominant limb seems to be more skilled at controlling the trajectory of the reach. Although, the nondominant limb seems to control final position and helps sustain a stable posture more effectively than the dominant limb. Typically, when performing asymmetrical bimanual tasks such as slicing bread or cutting a piece of paper, the nondominant limb stabilizes the object while the dominant limb controls movement of the utensil or tool. The dynamic dominance hypothesis has received further support from work examining the effects of stroke on reaching.[28]

Movements like reaching, incorporate and produce various joint torques. *Muscular* torque is produced via muscle contraction. *Intersegmental* torque is the motion produced at one joint as a result of muscular contraction at another joint. *Gravitational* torque is the force acting at a joint as a result of gravity. *Net* torque is the combination of all torques acting to move a joint. Sainburg[11] has shown that under similar speed and displacement conditions, the dominant limb produces reaching movements with less than half the muscle torque when compared to the nondominant limb. This has been supported by electromyographic recordings.[26,27] In essence, the dominant limb appears more efficient because it employs less muscular force and makes better use of interaction torques and advanced planning processes. Alternatively, the nondominant limb uses greater muscular force in the form of co-contraction and seems to rely more on feedback mechanisms for positional control and stabilization. Whether the differences between limbs, found in planar reaching,

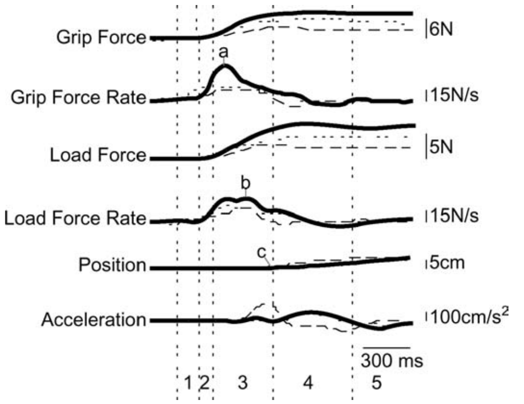

FIGURE 3. Sample data during a grip-lift task involving three objects of different weight (line = 600 g; dotted = 400 g; dashed = 200 g). (a) Relationship between grip force, grip force rate (a-peak), load force, load force rate (b-peak), position of the object in relation to the support surface (c-lift-off) and acceleration as the object is lifted. (b) Early phases of task; 1. finger contact; 2. preload phase; 3. loading phase; 4. transition phase; 5. static phase.

apply to vertical reaching or manipulative tasks needs further testing.

Minimizing Cost/Optimization

Cost functions are mathematical functions that describe the expense to a system relative to a particular variable. Theories of optimization propose that movements are specified to reduce cost and thus improve efficiency.[29–31] Figure 4 demonstrates the progression toward efficiency in infant reaching from early onset to two years of age. As infants learn to reach for objects, the hand path becomes progressively straighter and reaches are elicited with much less energy, thus reduced cost.[32] In adults, "efficient" coordination may be achieved by taking advantage of interaction torques or the passive mechanical interaction between different limb segments.[11] Although reciprocal activation of opposing muscle groups is considered more efficient for some tasks, other well-learned tasks demand muscle coactivation. Spencer and Thelen[33] found that adults displayed greater coactivation during fast vertical reaching movements. In essence, although the system may strive for efficiency, muscle activation patterns seem to vary depending on task constraints.

CHANGES AFTER PERIPHERAL NERVE INJURY

Immediately after PNI changes begin in the periphery and CNS, contributing to reorganization, physiologic recovery, and coordination. These changes will now be reviewed.

Neural Reorganization

Regardless of the cause of nerve injury, the central and peripheral nervous systems rapidly react and begin adapting to the reduction in sensory input.[34–37] These adaptations range from Wallerian degeneration peripherally to topographic rearrangement in cortical and subcortical structures.[1,2,36,38,39] The capacity of the nervous system to alter its organization in response to learning or lesions is regarded as *plasticity*.[40] Neural plasticity expands the boundaries of recovery from nerve injury.

Physiologic Recovery

Physiologic influences on neural recovery and reorganization include the timing of the nerve repair or reduction in compression and the integrity of the neural environment. For the nerve to regenerate the central axon must survive, the neural environment must support axonal growth, the axon must make contact with receptors, and the CNS must integrate signals from the peripheral system adequately.[41]

After a latency of about two to three weeks, a nerve that has been lacerated and repaired begins to regenerate. The regrowth rate in adults is about 1–3 mm a day or more for a nerve laceration/repair[42,43] and about 3–4 mm a day after a crush.[43] The timing for

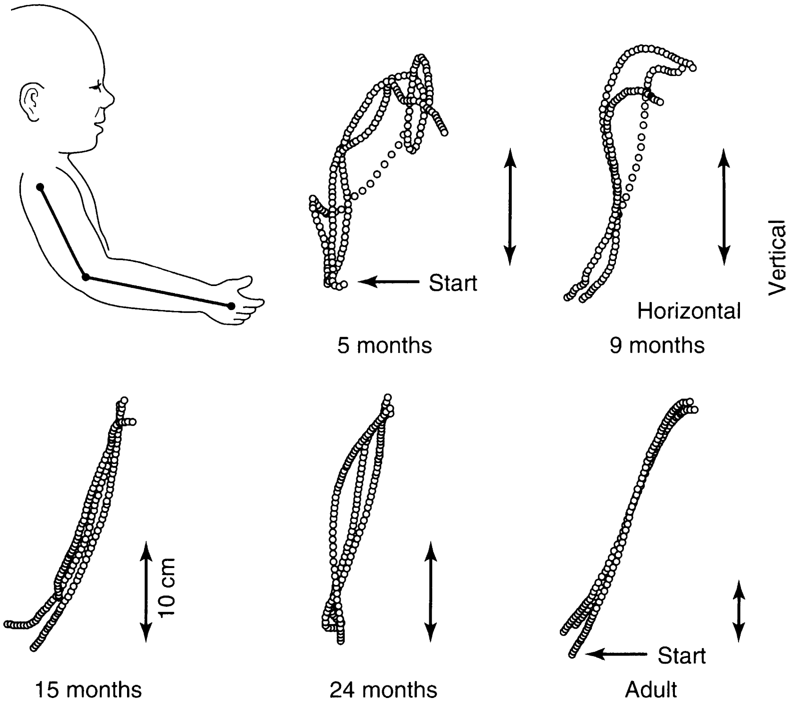

FIGURE 4. Progressive straightening of the hand path recorded during infant reaching in comparison to an adult. (From Konczak J, Dichgans J. The development toward stereotypic arm kinematics during reaching in the first 3 years of life. Figure 1. Exp Brain Res. 1997;117:346–54, reprinted with permission from Springer-Verlag.)

axon regrowth after relief from nerve compression is more variable.

Changes in the Somatosensory Cortex

Although reorganization can occur anywhere in the nervous system, the alterations that take place in the somatosensory cortex after PNI are well documented and may include:

1. *Migration* of cells that usually serve other parts of the body into deafferented cortical regions[44–46]
2. *Unmasking* or removal of inhibitory controls in the affected region[47–55]
3. *Strengthening* of existing subthreshold excitatory inputs and connections based on experience after injury[3,56–60]
4. *Subcortical reorganization* in regions that project to the cortex, such as the brainstem, thalamus, or basal ganglia[1,50,61–63] and
5. *Neurogenesis, sprouting,* and the construction of new pathways [64,65]

Both the sensory and motor systems respond to the alterations in sensory input and subsequent reorganization.[66] For example, during reorganization, innervated regions may experience greater sensitivity to sensory input than before a select nerve injury.[61,67] Thus, the face may become more sensitive to light touch after a reduction in sensory input to the thumb, because it gains representation in the cortex.[61]

Alterations in Sensorimotor Control

Motor control is affected by distorted or absent sensory input, as documented in patients with large-fiber neuropathy,[68–70] focal hand dystonia,[34] and dennervation.[71,72] Table 1 reviews the impact of PNI on motor control.

Due to sensory loss and muscle denervation experienced after PNI, the available *degrees of freedom* change including a reduction in motor units, muscles available and resultant joint motion produced. This change in degrees of freedom demands that alternative patterns or synergies be used. After median nerve injury, the thenar muscle group is usually compromised. Thus, grasp patterns might shift from precision to power grips or bilateral grasp patterns. With a low ulnar nerve injury, a visible Froment's sign (excess thumb interphalangeal joint flexion during lateral pinch) indicates that the adductor pollicis is denervated and the flexor pollicis longus is being recruited to pinch. Although compensatory efforts from remaining innervated muscles will aid function, coordination will often be reduced contributing to an increase in cost.

Absent or diminished somatosensory input distorts feedback mechanisms and may also impact anticipatory control. Sainburg and colleagues[69,70] found that proprioceptive deficits result in deficits in *interjoint coordination*. Specifically, they found individuals with large-fiber sensory myopathy had difficulty controlling the interaction torques imposed by a pantomimed movement of slicing bread. Without sufficient sensory information, reaching tasks that typically would have evoked reciprocal activation elicited greater coactivation and less efficient joint torque strategies.[69,70] Cole and colleagues[71] simulated median nerve compression at the wrist. Specifically, the authors used a clamp to induce compression and electric stimulation proximal to the carpal canal to generate sensory nerve action potentials. Deficits distal to the compression were documented using sensibility tests and measures of grip force scaling. They found that it was not until the compression caused a 50% reduction in sensory nerve action potentials that sensibility began to diminish and subjects began to use greater than 50% increase in grip force.

Secondary to impairment of the sebaceous glands of the fingertips after nerve injury, objects may seem more slippery. The increase in slipperiness and tangential loading of the skin leads to an increase in grip force; increasing the safety margin for slip and prolonging the phase durations of the grip-lift task, in particular the preload phase.[21] Despite previous experience and compensatory visual cues, this consistent increase in grip force has been well documented after a reduction in tactile feedback.[20,73–75] Interestingly, the grip-lift synergy seems to remain intact because the grip and load force continue to increase in parallel during loading.[21]

The changes that take place in the periphery and CNS immediately after injury to a peripheral nerve and attempts to reorganize are likely to influence or be influenced by motor lateralization/handedness.[1,2] Yet, because there is little to no research examining the difference in coordination between the dominant and nondominant limbs after peripheral nerve injury, one can only speculate. The importance of handedness and specialization in limb control may be best realized during the rehabilitation process. Injury to nerves that innervate the hands will impact manipulative tasks, thus handedness issues may play an important role. These issues warrant further investigation.

ASSESSMENT

Evaluation after PNI requires consideration of how impairments impact function. Yet it is often motor control problems that interfere with full recovery because of the influence they have on coordination. A useful guide to organizing the evaluation process is the three leveled, *task-oriented approach* by Shumway-Cook and Woollacott.[9] The levels are defined as:

impairments: neuromuscular/musculoskeletal constraints to movement;

TABLE 1. **Motor Control Strategies and PNI**

	Definition	*Examples*	*Implications for PNI*
Managing redundant degrees of freedom	There are many independent movement elements available to accomplish the same task. Successful management of this redundancy leads to smooth coordinated movement.	Various grip patterns can be used to grasp a soda can including a cylindrical grip, a spherical grip, or a lateral pinch. The capabilities of the individual, object properties, and context influence the movement elements used.	Injury to the median, ulnar, or radial nerve will reduce the degrees of freedom, restricting the range of prehension patterns available. For example, with a low ulnar nerve injury, the lateral pinch will be compromised because of the loss of intrinsic muscle control, reducing the ability to hold onto a key without excessive IP flexion.
Role of sensory information in feedback/anticipatory control	*Feedback* relays current sensory input to adjust movement "on-line" and uses previous input to influence subsequent movements.	*Feedback* — At object contact we receive tactile cues about its texture. We use this information to adjust our grip or squeeze force on the object. If the object slips sensory cues are relayed via tactile mechanoreceptors resulting in an upgrading of grip force.	The median and ulnar nerves provide the primary sensory information used during object manipulation. Impaired tactile and proprioceptive feedback often results in excessive grip and load forces as well as prolonged phase durations during the grip-lift task disrupting fine dexterity.
	Anticipatory control uses previous sensory information to plan movement in advance. Thus, feedback from one trial aids performance on the next.	*Anticipatory* — Preshaping the hand during reaching in preparation for object shape/size or grading the grip/load force to accommodate to an object's weight or texture prior to contact or lifts.	Although we can use vision to provide information about object properties before contact, distorted tactile and proprioceptive feedback may affect performance on subsequent trials impacting anticipatory control.
Motor lateralization/ handedness	The differential control between the dominant and non-dominant limbs during reaching.	During reaching movements, the dominant limb appears specialized for trajectory control (size, curvature, direction). The nondominant limb seems specialized for postural control or stabilization.	Injury to the dominant limb may necessitate dominance retraining. The tasks employed to retrain may need to be tailored to the specialization of the non-dominant limb or postural and stabilization components.
Minimizing cost	By making use of biomechanical factors the CNS seeks to optimize movements thus reducing the cost to move, which leads to greater efficiency.	When reaching toward a cup, one typically does the following: makes a direct hand path using the least amount of muscular force; takes advantage of intersegmental dynamics of the linked system; opens the hand just enough to accommodate the cup's shape and size and employs the prehension pattern best suited to achieve stable grasp points.	Any nerve injury that reduces joint motion will increase cost and decrease efficiency. Thus, with a high radial nerve injury; elbow, wrist and finger/thumb extension will be diminished. To reach for an object at table height one would need to externally rotate the shoulder and supinate the forearm. This path would be indirect and because of the awkward hand orientation, the object may not be secured.

motor strategies: sensorimotor control used to perform actions; and
function: the ability to perform essential tasks and activities.

Problems associated with each level of this approach are reviewed in Table 2. Most clinical environments are well aware of how to evaluate impairments (e.g., sensibility tests)[76] and function

TABLE 2. **Problem Identification: Median Nerve Injury at the Wrist**

Impairments	*Motor Strategy Limits*	*Functional Limitation*
	Redundancy	
Diminished or absent activation of muscles serving the radial side of the hand including the thumb, index, and long finger.	Reduction in available degrees of freedom and restricted repertoire of hand movement resulting in awkward use or incomplete cylindrical and spherical grip, palmar pinch and three-jaw chuck patterns.	Will have difficulty picking up small objects requiring thumb opposition such as coins. In-hand manipulation will be limited or absent. Compensatory patterns will be needed.
	Feedback /anticipatory control	
Proprioceptive deficits through thenar muscle group and radial lumbricals. If the sensory branch is affected, there will be sensibility deficits on the volar aspect of the radial side of the hand and friction at the fingertips will be reduced secondary to diminished function of the sebaceous glands.	Feedback—Sensibility deficits will lead to more frequent object slips and prolonged duration of phase during the grip-lift task. To compensate, grip force will be excessive.	Will have difficulty handling fragile and/or slippery objects even with functional splints. Performance on most prehensile tasks will be prolonged thus compromised unless vision is used to compensate. Stereognosis and in-hand manipulation will be restricted secondary to the motor and sensory impairments.
	Anticipatory control—grading of fingertip forces during grasp and release may be impaired.	
	Motor lateralization/handedness	
Impaired tactile and proprioceptive feedback. Anticipatory control may indirectly be affected.	There may be differential affects depending on whether the dominant or non-dominant limb is affected. Denervation, thus loss of muscular control and on-line sensory feedback, will reduce reaching and manipulative skill in both limbs. It is unclear how PNI would specifically affect this control.	Fine dexterity will be limited regardless of the hand injured. One could speculate that quick, direct reaching movements would be impaired in the dominant limb and the non-dominant limb would have difficulty stabilizing during bimanual tasks.
	Cost function	
Energy and effort used to reach for and manipulate objects will increase due to demand for compensatory muscular effort. Timed performance will be slower in both limbs	Slow, labored hand movements will predominate. Compensatory prehension patterns will likely increase effort.	The time employed to manipulate objects will increase impacting all functional fine-motor tasks. Also, the compensatory prehension patterns may be ineffective during select tasks.

(e.g., AMPS)[77] but are less cognizant of how to identify and assess motor strategies. These will be reviewed next.

Motor Strategies

Clinicians may be able to determine the impact of problems and assess improvements in motor control and learning by examining *adaptability*, *efficiency* and *consistency* during task performance.[10] The motor control concepts reviewed previously can be incorporated into these three broad categories as presented in Table 3. The most accurate means of capturing motor strategies are by documenting and interpreting movement behaviors through the use of expensive equipment and subsequent analysis. For clinicians, visual observation, video recording or the use of a stopwatch are much more feasible and affordable means of obtaining this information. Sample tools and methods used to measure motor strategies are provided in Table 4.

Adaptability

Adaptability is the ability to adjust control strategies to changes in task components or features in the environment given individual capabilities. The ability to adapt demonstrates how one learns how to manage redundancy in the system and how anticipatory and feedback control are used. Determination of adaptability is subjective and can only be inferred, based on response to task context or components.

Following nerve injury in older children and adults, prehensile problems may include:

1. Display of curved versus straight hand paths when reaching to targets
2. Coactivation during tasks that typically elicit reciprocal muscle activation
3. Overshoots or undershoots to targets
4. Incomplete or excessive finger opening when preshaping the hand to objects
5. The use of unstable grasp points on objects

TABLE 3. **Relationship of Motor Control Strategies to Motor Learning**

	Control of Redundancy	*Role of Sensory Information in Feedback and Anticipatory Control*	*Motor Lateralization/ Handedness*	*Minimizing Cost/Optimization*
Adaptability	Displays a range of movements and prehension patterns when performing the same task.	Able to reach directly to targets, preshaping the hand to any object property, avoiding object slippage or crushing in response to constraints or perturbations	The dominant limb may be better suited to adapt to alterations in task or conditions than the nondominant limb.	Coordination is smooth and quick regardless of task demands or movement employed.
Efficiency	Sufficiently manages the degrees of freedom required for select movements exhibiting synergistic patterns.	Displays quick reach, grasp, manipulation, and release components during prehensile tasks.	During planar reaching, the dominant limb seems to use less muscular effort and takes better advantage of intersegmental dynamics. Thus, it is quicker than the nondominant limb.	Exhibits direct hand paths when reaching to targets, taking advantage of biomechanical factors. Displays quick dexterous movements during timed dexterity tests.
Consistency	Retains and transfer the ability to manage the degrees of freedom on the same or similar task repeatedly. For example, the grip-lift synergy used during repeated lifts of an object.	Displays peak grip aperture (width) at a similar time and distance from the target during reaching. Displays the same phase duration during the grip-lift task.	The limbs would repeatedly display asymmetrical control features during reaching tasks.	Performs quickly and effortlessly on repeated attempts on the same tasks.

6. Excessive or insufficient grip/load forces and rates during manipulation
7. Awkward in-hand manipulation or an inability to move objects in one hand
8. Low endurance for sustained grip tasks

To ascertain how the degrees of freedom are managed and how somatosensory deficits and muscle denervation influence prehension, the clinician should attempt to elicit the various components of prehension, closely observing for the problems listed above. Specifically, the clinician could request the individual reach, grasp and lift a range of objects from light to heavy, rough to slippery and stable to fragile (e.g., hard plastic vs. styrofoam), placed in various locations with and without vision. Following a low median nerve injury, one would expect to see a limited repertoire of radial prehension patterns due to partial or full thenar muscle denervation and a reduction in thumb joint motion. Despite reduced motion, the individual may display sufficient compensatory grasp patterns or the ability to exploit the remaining degrees of freedom. If the injury were higher and also involved the sensory branch of the median nerve to the thumb, the diminished sensory input may result in deficient on-line feedback and possibly anticipatory control. Specifically, objects may slip or be squeezed too tightly or hand movements may be slow and awkward, suggesting there was insufficient input from tactile mechanoreceptors. The use of excess grip force may also contribute to quicker muscle fatigue and thus lower endurance for tasks demanding sustained grip.

Efficiency

Efficiency can be interpreted as performing tasks with minimal cost to the system as measured by energy expenditure and muscular force. Because nerve injuries often require the use of alternative muscle groups and grip patterns to perform fine-motor tasks, effort is higher and efficiency is often reduced. Movement speed recorded during functional tasks or dexterity tests like the Jebsen-Taylor Test of Hand Function[78] provide an objective measure of efficiency that can also be used to track recovery.

Consistency

Consistency is the repeatability of performance. To measure consistency, we can assess *retention* of performance after a period of time has elapsed and *transfer* or generalization of task performance given alterations in force requirements or timing.[79] To examine consistent use of prehension patterns, one could use the Sollerman Grip Test.[80] This five-minute test measures the quality of prehension used to

TABLE 4. **Sample Tools / Methods to Measure Motor Skill Learning**

Adaptability		*Efficiency*		*Consistency*	
Tool/Method	*Measurement*	*Tool/Method*	*Measurement*	*Tool/Method*	*Measurement*
Transfer test: observation or video-recording of a practiced prehensile task given altered force or timing	Document how force or timing was altered and tally the number of errors or successful trials	Timed **handwriting**	Speed	**Retention tests** after practice of specific prehensile activity	Tally of errors or number of successful trials
					Tally of number of days able to perform
Observation or video-recording of hand preshaping for objects of different size or shape	Time-code the videotape and document the degree and timing of finger opening for different objects	**Jebson-Taylor Test of Hand Function** *(Jebsen et al., 1969)*	Speed	**Sollerman's Grip Test** (Sollerman, 1984)	Scale of 1–4 in terms of quality of select pattern used.

secure select objects and grades this performance on a four-point scale.

INTERVENTION

Intervention for reach, grasp, and manipulation disorders due to PNIs is based on a task-oriented approach and involves three goals[81]:

1. Enhancement of resources to prevent secondary impairments
2. Promotion of sensorimotor control strategies
3. Increasing function through practice or alteration of task demands/context

The incorporation of all three goals into the treatment plan may enhance reorganization and improve coordination and function. Suggested in-

TABLE 5. **Intervention Strategies Based on Task-Oriented Approach**

Resources	*Motor Strategies*	*Function*
Reduce edema and pain	**Optimize motor strategies** Teach individual to optimize intersegmental dynamics and to take advantage of two-joint muscles (e.g., tenodesis) or use adaptive equipment/splints to accomplish it depending on recovery level	**Interlimb transfer** Use of contralateral limb to train injured limb
Splinting		
Techniques to increase soft-tissue mobility		**Constraint-induced therapy** Practice of tasks using involved limb for sustained period
Sensory re-education	**Feedback** Augment feedback while awaiting nerve regeneration	**Bimanual tasks** Limbs perform identical actions or coupled movements
Biofeedback/functional electrical stimulation	Verbal feedback and knowledge of results on performance may help with error correction	Limbs perform asymmetrical actions (stabilizer, or manipulator)
Strengthening activities	**Sensorimotor training** Use familiar tasks and objects to elicit previously acquired motor strategies to enhance consistency and use of anticipatory control	**Functional practice** Task specific for work, self-care or recreational tasks
	Use novel tasks and objects to demand new strategies be developed	Encourage generalization and transfer during activities of daily living and other functional tasks by altering force or timing demands
	Alter task and performance demands (forces/timing) to enhance *adaptability.* For example, alter object location (e.g., use wall or floor instead of the table-top for throwing, drawing, or construction tasks).	Tap into meaningful recreational tasks
	Use a timer to encourage increased movement speed thus *efficiency*	
	Use extended practice to reinforce *consistency*	

tervention strategies with consideration of these goals are provided in Table 5.

Enhancing Resources/Preventing Secondary Impairments

Most therapists are quite familiar with ways to reduce impairments and increase resources after nerve compression or repair.[82] Early in treatment, edema and pain are often addressed through well-known strategies. Patient education and protective sensory programs are reinforced to prevent skin injury while reinnervation occurs. Splints are issued to protect joints or promote function while awaiting regeneration (Figure 5). Biofeedback and functional electrical stimulation can promote or augment activation of muscle groups that are reinnervating. Once the nerve has regenerated sufficiently, strengthening and sensorimotor training programs can begin.

Promoting Sensorimotor Control Strategies

Although it is possible for hand function to improve steadily with regular use of the impaired limb, coordination does not always return so easily. Therefore, clinical methods to optimize control strategies, augment feedback, and foster reorganization through sensorimotor retraining and activity-based treatment are recommended.

Optimization of Control Strategies

Adaptation to sensory and motor loss postinjury may require exploitation of the available degrees of freedom to achieve movement goals. It is feasible for clinicians to promote greater *efficiency* (reduce cost) by teaching individuals to take advantage of the intersegmental dynamics of the linked segments of the upper limb, especially during reaching and release.[83] For instance, if the triceps muscle is denervated due to high radial nerve injury, elbow extension will be restricted. While awaiting reinnervation, the individual could be taught to reciprocally activate the anterior and posterior deltoid to passively move the elbow during planar reaching movements, thus taking advantage of interaction torques. A more distal radial nerve injury at the forearm level will affect the finger extensors. In that case, teaching a tenodesis pattern to release objects will take advantage of available two joint muscles in the linked system (finger flexors and extensors) to enhance function.

Splints or assistive devices can also be used to increase efficiency. The classic splint for radial nerve palsy[84] makes use of intact wrist flexors to control finger opening and intact finger flexors to control wrist extension via nonelastic string and loop mechanisms attached to a base splint (Figure 6). This splint may reduce cost to the system more effectively than the tenodesis pattern by decreasing the force demands in compensatory muscle groups and reinforcing a stronger radial digital grasp.

Individuals could also be taught to optimize control strategies, depending on handedness.[83] Because of the differential control between the dominant and nondominant limbs, methods to improve coordination could be customized to the specific control features of that limb. It is feasible that if dominance retraining for the nondominant limb focused on postural control and stabilization of utensils/tools it may elicit better control. For example, the use of wider pens and the performance of tracing tasks to initiate writing may enable the nondominant hand to achieve greater success. Methods that vary the treatment between the two limbs based on motor lateralization/handedness have not been well studied, thus require further investigation.

Supplemental Feedback

Because diminished somatosensory (*intrinsic*) feedback can limit success during prehensile tasks, most individuals avoid using the impaired limb. In an effort to prevent disuse, Rosen and Lundborg[85,86] developed an auditory feedback mechanism that replaces tactile input during fine-motor tasks while one waits for the nerve to regrow after repair. This type of intrinsic feedback could be incorporated into therapeutic activity and may contribute to neural reorganization while it is being used.

Once protective sensation is documented (4.31 Semmes Weinstein monofilament),[87] sensory re-education programs can begin. Although discriminating between squares of different textures is a good beginning, programs should gradually introduce objects of different shapes and textures incorporating the use of prehension patterns. Because of the difficulty individuals have maintaining secure contact on slippery objects, it may be useful to initially include objects with rougher surfaces (e.g., leather or sandpaper) to enhance stable grasp patterns and prevent slip when grasping and lifting. Objects with smooth textures (e.g., rayon) can be introduced later as sensory recovery progresses.

Augmented or *extrinsic* feedback can be provided in the form of knowledge of results (KR) and knowledge of performance (KP).[88] KR is information about the outcome and KP is the information about the movement characteristics that lead to the outcome. KR may be inherent in the task itself. For example, if a ball is tossed toward a basket and makes it in, the outcome is considered KR. Timing an individual's performance on select tasks also provides KR and fosters greater efficiency. KP is often given verbally as when a clinician says, "You did not

FIGURE 5. *Example of dorsal block splint to prevent metacarpal phalangeal hyperextension, worn by a child who sustained a cervical spinal cord injury.*

FIGURE 6. *Radial nerve splint. The splint will extend the fingers through active wrist flexion and extend the wrist through active finger flexion.*

secure the glass because your fingers were not opened wide enough before you touched it. Thus, the points where you touched the cup were too close together instead of opposite and stable.'' Because of the importance of augmented feedback and other motor learning concepts have in rehabilitation they should be given consideration when treating PNIs.[10,89]

Activity-based Treatment

Regeneration and reorganization of neural processes after injury is likely an activity-dependent process.[3] Yet, the specific neural mechanisms responsible for the changes may vary.[56,57,91] Because meaningful goal-directed activity engages the attention and motivation of the patient it may promote greater use of the hand and limb.[3,4]

Sensorimotor training incorporates a wide variety of methods such as tactile discrimination and stereognosis training. Byl and colleagues[4] had individuals with focal hand dystonia participate in a wellness program and supervised repetitive sensorimotor training activities for 12 weeks. They documented substantial improvement in somatosensory hand representation, target-specific hand control, and clinical function including sensory discrimination. They provided evidence that this form of treatment effectively reverses the negative consequences of focal hand dystonia perhaps through CNS reorganization.[4,60,90] It may be implied that sensorimotor training for PNIs would have a similar impact, yet this needs further support.

Familiar and novel objects are useful clinical tools for promoting consistency and adaptability. Familiar objects that elicit a range of prehensile patterns capitalize on the retrieval of existing memories for use during anticipatory control.[92] Repetitive practice of tasks using familiar objects and tasks may help compensate for impaired feedback and promote *consistency.*

Introducing novel objects or altering task demands to vary the degree of muscle recruitment or prehension pattern needed may enhance *adaptability.* Simple changes in task location and constraints; from a table-top task to one which demands the use of the wall or the floor may be challenging yet within range of an individual's capabilities. For example, before tossing a ball to a target the clinician could demand that the individual reach to the ground or into a basket before throwing. Drawing activities could be done with the paper secured to the wall introducing gravity constraints engaging the shoulder and trunk which may aid task performance. Careful design of treatment strategies with consideration of individual capabilities, the use of familiar and novel objects/tasks and varied environmental constraints has the potential to alter interjoint coordination demands and thus foster new motor control strategies.

Methods to Increase Function

A few popular strategies may effectively promote function in the involved upper limb and hand after nerve injury, including 1) interlimb transfer,[93] 2) bimanual training,[94] and 3) constraint-induced therapy.[95,96] Although these methods have been found effective primarily after central neurologic lesions, they may also be efficacious after peripheral nerve lesions, especially if they are integrated into meaningful goal-directed tasks.

Interlimb transfer involves the use of one limb to affect performance in the other limb during novel tasks. This method is supported by many studies including those investigating object manipulation in children with cerebral palsy[97] and mirror writing and reaching tasks in typical adults.[93,98–101] Research supports asymmetrical transfer of adaptation to changes in visual-motor demands or inertial dynamics of the limb.[93,98,100,101] The primary direction of transfer (dominant to nondominant limb or vice versa) appears to vary with the type of adaptation, whether visual or dynamic. It is plausible that after nerve injuries therapy programs could capitalize on features of interlimb transfer, but this needs to be studied further.

One could assume that *bimanual tasks* would be quite effective at promoting recovery, given the hemispheric connection through the corpus callosum, binocular visual mechanisms, and the redundancy in sensorimotor systems.[102] Because the involved limb is not required to do the task alone, the demands are reduced and so might the effectiveness.[103,104] However, this form of treatment has been used for years clinically and has received support in the literature after central neurologic lesions.[94,105,106] The benefits from bimanual activity may occur through interlimb transfer, as discussed earlier, or other processes. Rose and Winstein[107] suggest that to maximize the benefits from this form of treatment, the specific capabilities and task components should be considered before prescribing it. If supported with clinical research, bimanual training may be effective to promote function after PNI.

Constraint induced therapy (CIT) has successfully been used with patients who have sustained strokes[96,108] in those born with cerebral palsy[109,110] and in individuals with focal hand dystonia.[95] This type of intervention constrains movement in the noninvolved limb for a period of time while demanding more function from the involved limb through shaping tasks. Transcranial magnetic stimulation studies have shown that CIT results in cortical reorganization after stroke[111,112] and focal hand dystonia.[95] Although the use of CIT after PNI has not been well studied, it may be a potent method to enhance function.

In an effort to help individuals return to work, self-care, and recreational tasks with success, it is vital to encourage task-specific practice and experience with generalization and transfer of functional tasks.[92] Engagement in organized practice, as introduced in a clinical environment and carried over within a home program, may help individuals to incorporate new motor control strategies into tasks and reinforce learning. Given sufficient, carefully planned practice sessions, individuals may be able to return to previous activities without difficulty.

SUMMARY

Clinicians have the unique opportunity to make a tremendous impact on prehensile recovery after nerve injury. Although impairments and function are very important issues to address in treatment, intervention for motor control and learning problems may aide the transition from coordination deficits to recovery of sensorimotor control. The implementation of innovative methods to improve function while awaiting neural regeneration is one way to make a difference. This can be accomplished by introducing methods to optimize movement strategies and through the provision of supplemental feedback. Once regeneration has begun the use of meaningful but carefully planned training sessions such as that used after focal hand dystonia or central neurological lesions may foster effective neural reorganization and lead to greater functional recovery.

To make a bridge between research and clinical practice clinicians need to keep abreast of current findings on neural regeneration and reorganization. More studies need to be conducted documenting the efficacy of training methods aimed at promoting neural reorganization, coordination and function. With greater knowledge and expertise we may be able to prevent inefficient compensatory strategies from hindering prehensile recovery from peripheral nerve injury and promote greater sensorimotor control.

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