Sensory Substitution/Multi-sensory Correlation in Physical Rehabilitation Science

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Abstract

Assessing outcomes for extracorporeal orthotic and prosthetic clinical and technological intervention is fairly straight forward: just ask. Of course, the resulting subjective interpretation (ratings) might not fully capture or accurately reflect the underlining biological issues involved in physical restoration and rehabilitation of individuals with desensitized or missing limbs. Further, such subjective inquisition does not represent "hard" science, and the results of this method of inquiry will doubtlessly be less than wholly convincing to third party payers. A reproducible, consistent and (most importantly) predictable method for scientific testing or proving that any one intervention modality is preferable to any other needs to be developed. To do this, we need to find answers to the following questions. What are the underlining biological issues involved in physical restoration and rehabilitation? What makes a mechanical device biological, and what is the essential role of applied bio-mechanical engineering in physical rehabilitation science and medicine? The answers to these questions lies in the understanding of how applied bio-mechanics and neural mechanisms interact to facilitate correlation of sensory perception skills with normal body imagery skills and the acquisition of sensorimotor skills necessary for the resulting optimal mechanical design and utilization of orthotic, prosthetic and robotics devices.

Introduction

Rehabilitation science and medicine researchers are coming to realize that extra-corporeal orthotics and prosthetics are sensory as well as functional substitution devices and that these substitutions are equally important and mutually beneficial. Researchers have identified a high correlation coefficient between normal body imaging and acquired sensory perception skills with enhanced orthotic/prosthetic control and manipulations skills.

The late neuroscientist, Paul Bach-y-Rita MD. PhD., hypothesized in the 1960's that "we see with our brains and not our eyes", and has since researched sensory substitution and sensory perception. This research has lead to the development of "Brain Port" that allows the visually impaired to "see" with their tongues. Optical images picked up by TVSS cameras are transformed into electrical energy that can be mediated by skin receptors under the tongue, and effectively substitutes the two million optic nerves that normally transmit optical signals from the retina to the brain's primary visual cortex. Michael Merzenich PhD. (Neuroscience, UCSF) believes we can make smarter prosthesis when we're smarter about integrating neuroscience with engineering and medical science. Dr. Merzenich believes that researchers cannot overestimate the capacity of the human brain to restore function, to be trained, to make up what's been lost in extraordinary ways, and with the help of prosthetic devices, sensory information can continue to flow into the brain from the peripheral nervous system. Research shows that the brain will learn to use that information for motor control.(1) Kristin Farry PhD. (Excalibur Technical Services) has taken it one step further with quantitative detection of "phantom" limb sensation and its measurable effect on upper limb prosthetic manipulation and control. Dr. Farry used the subjects' comments about when they became aware of the "phantom" limb plus motion start setting and SNR's to estimate the point at which the "post phantom" data set began. She found four potentially significant quantitative indicators of a "phantom" limb development: increased signal to noise ratio, decreased delay between motion prompt and myoelectric response, decrease in motion error and increase in motion clarification accuracy. Myoelectric data suggests that muscles were coordinating in more distinct motion specific patterns after the phantom sensation began and may be correlated to a very active imagination and increased proficiency in mental visualization with practice.(2) Using positron-emission tomography (PET) and fMRI analyses, Marcus Raichle (Radiology/Neurology, WUSM. St. Louis) has determined that a large fraction of the overall brain activity - from 60-80 percent of all energy used by the brain – occurs in circuits unrelated to any external event or stimulus – leaving too little neural activity to generate a meaningful perception on their own (While six million bits are transmitted through the optic nerves, only 10,000 bits make it to the brain's visual processing area, and only a few hundred are involved in formulating conscious perceptions). Dr. Raichle's findings suggests that the brain spends most of its resources in making constant predictions about ones' body and its relationship to the environment in anticipation of paltry sensory input reaching it form the outside world. (3) A compelling argument can be made that sensory perceptions (to include "phantom" limb sensations and motion specific muscular patterns) are related to and result from predictive and anticipatory skills as well as imagery skills.

Medical and biomechanical technology has advanced to the point where lost arms and legs can be replaced with artificial ones. Electrical and mechanical engineering, combined with suitable aesthetics, has the potential of making the artificial substitution device (prosthesis) with the same operable range of basic or rudimentary function as the limbs they replace as long as the replacements have a suitable interface to the remainder of their user's body. There have been several successful attempts to allow a user of these prostheses to control them in a similar manner as the limbs they replace. Until recently however, not much attention has been paid to the other half of this sensorimotor circuit, namely feedback of sensation from these limbs to the user. Even though an amputee may regain the use of lost limbs, sensory impressions of those limbs still remain elusive. Sensory impressions of and from the substituted mediation modality are relevant to clinical O&P because orthotic-prosthetic control and manipulation skills are essentially acquired sensorimotor skills. Mastery of sensorimotor skills or patterns is kinesthetic. Kinesthesia is defined as awareness or perception of motion. Awareness or perception of motion can be described as an interactive and acquisitive relationship between body imagery skills and sensory input and motor output anticipatory skills. Therefore, assessing and measuring the combined and complex biological, physiological and mechanical effect of applied loads on and from the O&P device are directly associated with assessing and measuring anticipatory skills. As a matter of provisional conjecture, measurement of one can be most meaningfully acquired with the coinciding measurement of the other.

The potential rehabilitation value in orthotic-prosthetic biomechanical and physiological design, as well as clinical (therapeutic) intervention, can be measured by how it affects the fundamental issue of accommodation and facilitation of ones' individual and unique capacity for neuromuscular and neuropsychological voluntary interaction with ones' environment. Starting as soon as possible in the rehabilitation process, these voluntary control mechanisms should be developed and coupled (paired or repaired) in "balance" to optimize, among other things, orthotic-prosthetic sensorimotor skills associated with control and manipulation skills. This paper examines the interactive and acquisitive relationship between associative (contingent) sensorimotor skills, body imagery skills and natural substituted sensory perception skills and its practical application in and unifying effect on neuroscience, biomechanics and contemporary orthotics/prosthetics and robotics clinical practice.

Methods

A preliminary study was conducted at Medical Center Prosthetics (Houston Texas) from July 1979 thru Sept. 1983 to determine optimal loading of lower limb early post-surgical removable and non-removable weight bearing dressings. Among other loading determinants, degree of wound apposition, medical status of subjects, magnitude or amount of loading and duration and cycling of loading were observed and analyzed. An analog weight monitoring device was developed by Medical Center Prosthetics to indicate when threshold and set point weight bearing values were attained by the subject. The threshold and set points were calibrated using a bathroom scale and an audio indicating multi-axial ankle-foot would sound an audible cue or alarm when the calibrations were reached or exceeded.

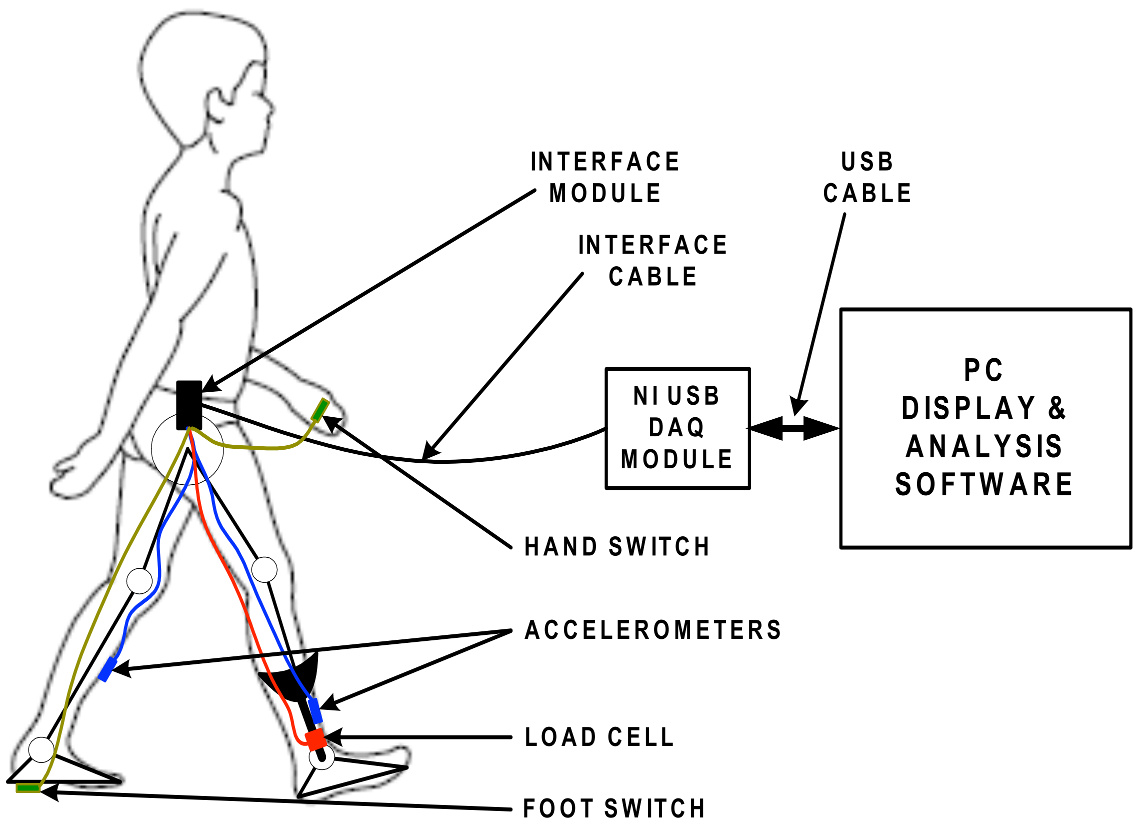
The multi-axial audio indicating ankle (MAAIA) load bearing monitoring device was initiated on the average of 6 - 8 weeks post-operatively, or when the suture line was approximately 80% apposed and the sutures were removed. The study was conducted in either an acute care or extended care hospital setting under the medical direction and supervision of the attending physician and/or in-house physical therapist.

From January 1985 thru June 1987, a follow-up study was conducted by Wilson Prosthetic Associates (Houston Texas) to more accurately determine how long and under what conditions soft tissue stabilization would occur. The 19 subjects selected for this study were divided into two groups: trans-femoral and trans-tibial. These two groups were further divided into trauma and disease related ablation. All subjects were independent and unassisted ADL prior to ablation surgery, and deemed capable of regaining their pre-surgical ADL status subsequent to restoration and rehabilitation. All subjects received prosthetic care under medical supervision until they regained pre-surgical ADLs as well as soft tissues stabilization for a period of 3-4 weeks in response to the level of activity characteristic of ADLs and when contained in an anatomically and physiologically correct hydrostatic socket. Subjects were required to attain a wearing schedule of 12 - 14 hours/day, and to be on their feet approximately 50% of the time, at which time medically supervised preparatory prosthetics was terminated. The subjects were subsequently provided definitive prosthetic care under the supervision of the attending prosthetist in the out-patient prosthetic clinic. Delineation of definitive prosthetics was based on preparatory iteration.

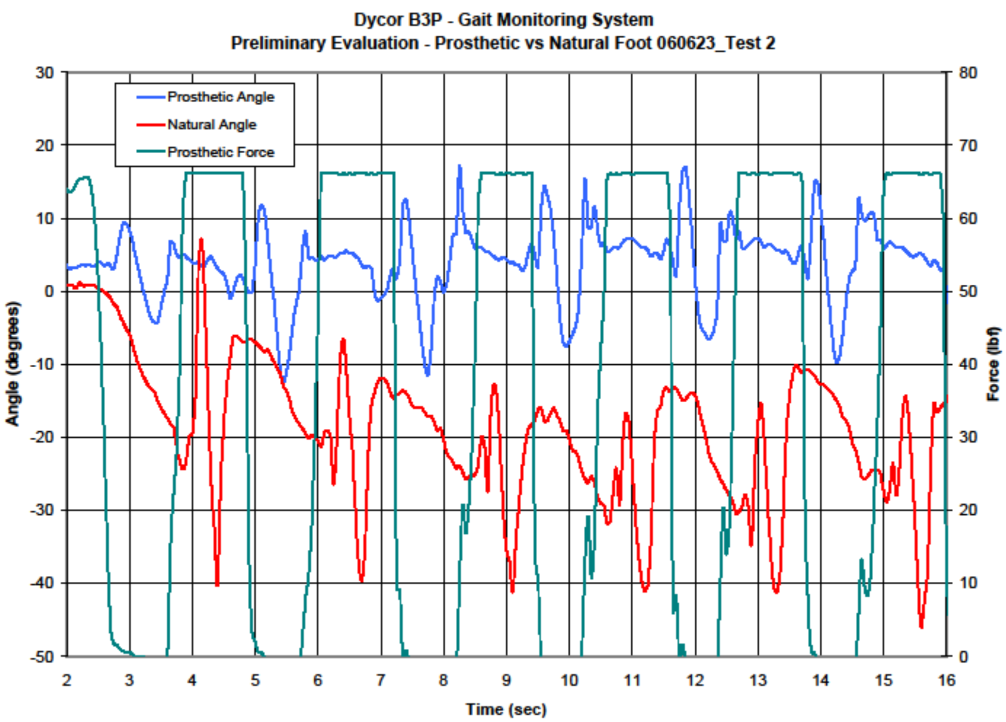
In 2006, an experimental neurocorrelagraphic device was developed to measure the subject's ability to anticipate or accurately predict when threshold and set point calibrations would be reached when loading the prosthetic socket. The device consists of accelerometers, load cells and foot switches on both affected and contra-lateral lower limbs as well as a manually activated timing switch. Information from these sensors and timing switch is fed into a PC for display and analysis. In effect, what is being taught, measured and recorded is the subject's ability to correlate normal body imagery skills with afferent emanation bio-mechanically and physiologically engineered into the substitution device. This bio-engineered afferent emanation can be thought of as a source or form of "reafferentation" because the subject is correlating identical afferent input generated primarily from the residuum that would otherwise be generated from the missing parts of the lower limb. Perception of "reafferentation" and conceptualized correlation of body imagery with sensory input can be initially augmented or reinforced with optical input provided by the subject viewing real time data appearing on the PC and acoustical input emanating from speakers. Acoustical input is characterized by three different frequencies; a low frequency that indicates the approach to threshold force, and pleasant frequency that indicate exact threshold calibration and a very unpleasant frequency when the set point has been reached and/or exceeded. Haptic input from the residuum is reinforced only initially and only for short periods of time with optical and acoustical input because optical and acoustical input are usually more familiar to the subject and can initially be more easily associated with imagery skills or pseudo sensations. There was no attempt made to permanently supplant or supersede natural "reafferentation" from the residuum or from any other part of the body with contrived perceptual distortion modalities. Perceptual illusion or optical distortion modalities are currently in vogue, but their lasting benefits in rehabilitation are still in question. The neurocorrelagraphic device is designed as a teaching and learning tool, and can be temporarily attached to both the sound limb and prosthesis, and can be easily detached. (Neurocorrelagrams could be transmitted in real time to the supervising medical agent or rehabilitation specialist to determine whether or not the subject can safely, consistently and predictably perform specific sensorimotor skills, such as independent transfers in an skilled nursing facility.)

Neurocorrelation coefficients were monitored in reference to, among other things, dynamic changes in soft tissue volume. It was noted that soft tissues stabilization occurred at approximately the same time neurocorrelation coefficients stabilized (25-34 weeks post-operatively). An intuitive and plausible explanation for this coincidence might be considered straight forward: pressure emanating from the structurally stable socket are being consistently and predictably mediated and conveyed by receptors in the stabilized soft tissue "structure" of the residual limb. However, the apparent mutual and reciprocal interaction between histological dynamics and mental concentration and conceptualization of body imagery and sensory perception may not be so easily explained.

DYCOR B3P SYSTEM



The neurocorrelagraphic display or printout indicates relative angles of the sound limb on the vertical axis (shown in red) and relative angles of the affected or ablated limb (shown in blue). Time (in sec.) is indicated on the horizontal scale. The green line and right vertical axis indicates loading. Manual activation of the hand switch is indicated by small timing markers appearing on the graph relative to both vertical and horizontal axes. Both horizontal and vertical axes can be "stretched" to accommodate extreme accuracy. For instance, the horizontal axis can be adjusted to accurately measure timing skills to within 5 ms. and can also be "compressed" to measure multiply cycles (as illustrated). An example of how the rehabilitation specialist might utilize neurocorrelagraphy in physical rehabilitation would be to ask the subject to anticipate a relevant and perhaps critical sensory event that uniquely pertains to a specific biomechanical characteristic, consideration or property. Perhaps the rehabilitation specialist determines that a certain perceived relationship between angulation of both the affected and contra-lateral limb is crucial in the optimal positioning of the prosthetic knee at terminal impact. The specialist would then train, measure and record the subject's ability to place the timing marker on the graph at exactly the right time and place where angulation shows equal and opposite magnitude. Several such scenarios (a potentially infinite number) were created to better understand the relationship between neuromechanisms and applied biomechanical and physiological design characteristics unique to each individual prosthetics subject.



Results

A great deal of medical and rehabilitation science was gleaned from these studies. Initially, how post-surgical weight bearing can be used to promote wound apposition and maturation and facilitate reduction of residual limb inflammation and swelling. For example, to obtain soft tissue stabilization in an anatomically correct socket and in response to full time pre-surgical ADLs required 25- 34 weeks of clinical preparation. To maintain an anatomically and physiologically correct hydrostatic socket (particularly in response to soft tissue atrophy) required socket iteration once every 1.3 weeks for trauma related trans-tibials and every 2.5 weeks for disease related trans-femorals. It is also interesting to note that costs of preparatory prosthetics contributed to 60% of the total costs of prosthetic care. (The results of the first stage of this study were made public, and the Audio Indicating Multi-axial Ankle (MAAIA) was commercialized and used widely by the O&P and physical therapy communities throughout the 1980s until replaced by more advance designs for measuring and recording loading activities.)

What was not anticipated in the initial study was the extraordinary "animating" effect this study had on the subjects. More specifically, there was an unexpected and strong correlation between the subject's ability to safely and enthusiastically benefit from early post-operative weight bearing and their reported interest in and demonstrated and measured ability to predict exactly when the audio indicator would activate. In other words, the subjects appeared to be very interested and highly motivated in anticipating when they were transmitting the exact amount of force through their body to activate the audio indicator. There also appeared to be a relationship between proficiency in acquired anticipatory skills and the maintenance or attainment of a more natural feeling "phantom" Limb and this more natural feeling more closely coincided with simultaneous mechanical function of the prosthesis. There also appeared to an inverse relationship between anticipatory proficiency and the presence of phantom and/or residual limb pain.

Discussion

Applied neural science and bio-mechanics

We have all asked ourselves why do some orthotic/prosthetic medical patients and/or O&P physical rehabilitation clients experience so much difficulty with, while others breeze through, orthotic and prosthetic physical restoration and rehabilitation? All things being equal, the problems are not always directly related to physiology, anatomy, histology, mechanics or psychology. It is the premise of this paper that some of the problems our clientele experience are often associated with the bio-mechanics and neuroscience aspects of O&P restoration. So let's take a closer look at bio-mechanics and neuroscience and the potential influence their interactive roles have in successful O&P treatment outcomes.

The O&P profession has historically defined an orthosis and prosthesis as a functional substitution device. Since my initial introduction in 1966 to orthotics and prosthetics, I have witnessed advances in clinical technology I never imagined possible. I think for us to continue moving forward at an ever increasing rate of clinical and technological innovation, we need to familiarize ourselves with the neuroscience aspect of our endeavor and begin thinking of orthotic and prosthetic restoration as sensory restoration as well as functional restoration; to think of a prosthesis and orthosis as not only a functional substitution device, but also as a sensory substitution device and that the value of these substitutions are equally important, mutually beneficial and wholly inseparable.

Sensory Substitution (**"Reafferentation" or afferent augmentation)**

Gaining an understanding of how information from natural receptors is integrated into the activation of muscle systems is only part of the bigger picture of sensory substitution and multisensory correlation. Our mental construct that comprises the sensory impressions, perceptions and ideas about the dynamic organization of ones' own body and its relations to that of other objects makes up the other. The body is represented in the human brain in various ways, and such representations are utilized in the perception of static and moving bodily parts, the understanding and imitation of motor acts and the conceptualization of egocentric identity and individuality. Within the context of a sensorimotor approach to understanding the nature of sensory experience, a main concern lies in studying the process by which subjects attain mastery of sensory perception from a substitution device. A series of five learning stages has been postulated by researchers at the Université Paris. (4) The first stage, **contact**, involves the subject learning the sensorimotor skill necessary to maintain and control perceptual contact with a stimulus. The second stage, **exteriorization,** involves the subject coming to experience the stimulus as no longer located at or in the receptor modality that conveys it (eye, ear, skin, residuum) but as corresponding to an outside physical entity, such as a prosthesis or neuropathic limb. The third stage, "**spatialization",** involves attribution of a spatial location for the experienced entity, with coherent understanding of its relation to the body. **Comprehension** involves being able not simply to spatially locate, but also to recognize the entity as a perceptual object among possible alternate objects. **Immersion** is the state where the subject possesses all these abilities and feels he or she is physically immersed in an environment populated by objects that can be perceived through the substituted reception modality.

These learning stages specifically involve two major areas of the brain, the parietal lobes and the cerebellum. The parietal lobes can be divided into two regions with different functions. The first region processes incoming sensory information and the second region is concerned with integrating processed sensory input with existing knowledge and understanding. The Postcentral Gyrus, within the parietal lobe, is responsible for somesthesia (somatognosis), or body sensation. This area of the cortex receives input from the somatosensory relays of the thalamus and represents information about touch, pain, temperature sense, and limb proprioception (limb position). The second functional region of the parietal lobes constructs a spatial coordinate system to represent the world around us. Individuals with damage to the parietal lobes often show striking deficits, such as abnormalities in body imagery and spatial relations.

The cerebellum is the area of the brain that plays an important role in the integration of sensory perception and motor output. Many neural pathways link the cerebellum with the motor cortex—which sends information to the muscles causing them to move—and the spinocerebellar tract—which provides feedback on the position of the body in space (proprioception). The cerebellum integrates this pathway, using the constant feedback on body position to fine-tune motor movements.

Exteriorized Neuropsychogenic Proprioception

The second learning stage of substituted sensory perception, **Exteriorization,** is of particular interest because it is not only neuropsychological manipulation of natural as well as artificial sensory substitution (input; such as vibrotactile, tactile-visual and electrocutaneous stimulation), but also represents volitional (autonomous) sensory interpretation. Sensory information emanates from the substitution device, is mediated or conveyed by sensory receptors, particularly those receptors adjacent and nearest to the orthotic/prosthetic interface, and is then processed and interpreted by the brain. An experimental neurocorrelagraphic device has been developed that, among other things, trains the user to exteriorize sensory perception as well as trains the user to imagine what they would like to feel, and at the same time, feel what they try to imagine. In the prototype configuration, the neurocorrelagraphic device is designed to facilitate and measure (referred to as neurocorrelagraphy) neural (multisensory) correlation in (of) the neuropathic and transtibial lower limb. What we are correlating is imagery and natural sensory substitution or natural afferent augmentation, and this neural correlation is referred to as exteriorized neurosychogenic proprioception (ENP), otherwise defined by the ubiquitous and somewhat pejorative term "phantom" limb sensation. The following neural correlation theory has been postulated to explain how neurocorrelagraphy and the brain might interact to facilitate ENP. This theory needs to be further scrutinized and otherwise reviewed by individuals interested in and familiar with this and other neural scientific and bio-mechanical concepts relating to this theory.

ENP Neural Correlation Theory

ENP utilizes sensory perception in much the same way language utilizes words. Words can be interchanged as long as symbolic interpretation of words remains the same (synonymity). Likewise, afferent mediation can be substituted as long as the substitution is imagined to be the same. Imagery is the first step in "enactively" facilitating ENP and implementing neurocorrelagraphic measurement of anticipatory input. The neurocorrelagraph user (subject) must imagine normality regardless of his or her physical state of being and degree of desensitization. Imagination is analogous to symbolic interpretation. Anticipation is the next critical step. Neurocorrelagraphy trains, measures and records the users' ability to anticipate specific events, in this case kinetic and kinematic activity based on substituted afferent mediation. Correlation is the third critical step. The neurocorrelagraphic subject learns to associate augmented sensory perception and proprioception with the image of normality in such a way not to be expected on the basis of chance alone. Neurocorrelagraphy facilitates a mutual and reciprocal relationship between imagination and sensory perception and proprioception by anticipating what the image of normality is actually doing and how the correlating afferent augmentation will be perceived. The theory of exteriorized neuropsychogenic proprioception is embodied in the previous sentence. **Imagination, anticipation and neural correlation are inextricably linked in ENP and imagery and sensory perception cannot be conceptually correlated without anticipation.**

History of Neuropsychology

Gaining an understanding of neuropsychology and neuropsychological technologies will help us understand the field of neuroscience as it applies to bio-mechanics and clinical orthotics/prosthetics and robotics. Neuropsychological technologies collectively describe a diverse group of applications and hardware that are used for the assessment and rehabilitation of brain and behavioral relationships. These technologies share a common history, common properties, and a common set of problems in their development, validation, deployment and outcome effectiveness.

P.O. Hebb was apparently the first to use the term neuropsychology in the late 1940's, and the term is used to describe the conveyance of clinical psychology and behavioral and cognitive neuroscience focused on the discovery, understanding and treatment of brain function and behavioral patterns. The first formal neuropsychology doctoral program was established in 1973 at the University of Houston.

Origins of Neuropsychology Technologies

Neuropsychological technologies are the result of integrating psychology with bio-engineering, such as neuromechanical, bio-mechanical and biomedical technologies. They are in essence the neural science of psychology beginning with the brass instruments of the earliest psychologist and including psychometrics, brain imaging, educational, computational, cognitive science, biomedical and bio-mechanical devices.

Brass instruments consisted primarily of clocks to measure reaction time and the speed of cognitive processes. From the 1920's-1970's, apparatus was made available for sensorimotor and cognitive assessment and primitive computation.

Brain Mapping

Wilder Pennfield began brain (also known as neural) mapping in awake humans using direct electrical stimulation of the brain. This led to the development of electro-encephalography (EEG) machines which in turn led to parallel development of functional brain imaging technologies and metabolic imaging, and most recently, near infrared spectroscopy (NIRS). Although EEG remains within the technical capacity of the individual researcher, clinician or department, these newer technologies for functional brain imaging have become so expensive and complex that only the largest institutes can manage their staffing and support. Neuropsychologists still play a major role in developing cognitive probes so that the images could be linked with millisecond precision to the activating stimulus. To circumvent this ivory tower syndrome, neurocorrelagraphic technologies have been developed that are geared to contemporary orthotic and prosthetic practice and operable within the confines and limitations of existing personal computer capacity. The purpose of the empathy training section of this paper is to introduce the O&P clinical practitioner and other physical rehabilitation specialist to bio-mechanical and neural scientific principles and concepts related to the more successful outcome of clinical orthotic/prosthetic technological intervention strateges without any additional new technology, but only with the ability to understand these precepts as they apply them to their existing daily practice.

Calculations relating to spatial awareness, balance, intention and timing, among other things, are translated into signals forwarded to the motion-planning area, premotor cortex and supplemental motor area of the brain, which in turn send instructions to the primary motor cortex, which causes the muscle to contract. Proprioceptive feedback passes through the spinal cord to the cerebral cortex and sub-cortical circuits in the cerebellum and in the basal ganglia to update motor commands. (5) The premotor cortex as well as the parietal lobes are components of the cerebrum. The cerebrum is concerned with sensation and interpretation of sensory impulses and all voluntary muscle activity. It is also the seat or center of consciousness and is the center of the higher mental faculties, such as memory, learning, reasoning, judgment, imagination, anticipation, intelligence and emotions. The cerebrum is often referred to as the higher brain. When contemplating sensorimotor activity, areas in the premotor cortex involved in performing the activity switch on, suggesting that we mentally rehearse what we do – a practice that helps us learn and understand imitation of motor acts.(6)

Activity in the premotor cerebral cortex is volitional and within our conscious control. We rehearse our activities in this area of the brain. Other authors have referred to this planning or rehearsing function of the premotor cortex as resolution, internal modeling, choreography, being poised for, predicting and anticipating. The more expert people become at specific motor patterns the better they can imagine how that pattern feels. True mastery of sensorimotor patterns is kinesthetic and requires a muscle sense or motor imaging in the brain's motion-planning area. (7) The ability to perceive extent, direction or weight of bodily movement (inertia) through space requires sensory input relating to motor function. It is the thesis of this paper that enhanced sensorimotor and imagery skills associated with prosthetic function (control and manipulation) are directly attributable to proficiency in simultaneous anticipation of sensory input and related motor output. It may well be the process of anticipation (confluence) in the premotor cortex that ultimately leads to multisensory correlation of imagery and sensory perception.

Artificial Sensors vs. Natural Sensors

Instead of using artificial sensors in the prosthesis, use the body's own natural receptors. These come pre-installed, no assembly required, do not require battery power, are not prone to mechanical or electrical failure and have been optimized through millions of years of natural evolution. Natural receptors provide cognitive feedback to the user that more accurately replicates communication with the brain. (8) Using natural receptors already present in the body is an attractive approach because it avoids the need to strap artificial sensory devices onto the body or the prosthesis, which could get in the way of manipulating the prosthesis and which, together with required lead wires, might not be cosmetic enough to be acceptable to the physically challenged population. More importantly, natural receptor communication with the brain is particularly effective when exteriorizing and "spatializing" sensory perception. The most advanced artificial sensor can process 32 simultaneous signals. In contrast, the fingers of the human hand have an estimated 17,000 touch or pressure mediating receptors, or 200-300 receptors per cm2. With natural receptors, the sensorimotor loop is completed in approximately 70 ms. (9)

Our clinical experience with neurocorrelagraphy is somewhat consistent with the findings of Haugland & Sinkjaer. For example, the sensorimotor loop involved in the prediction or anticipation of transtibial prosthetic heel contact can conceivably be reduced (with training) to 30 ms. or less. Sensorimotor information regarding spatial relations, orientation and geometric form emanate from the mediation substitution device, and is conveyed (or mediated) by natural receptors, particularly those receptors at the orthotic/prosthetic interface. Elapsed time for the sensorimotor loop remains somewhat consistent regardless of emanation alteration or manipulation. In other words, predictability of prosthetic function (such as heel contact or perhaps equal distribution of weight on the plantar surface of the prosthetic foot) is not excessively altered by substituting or interchanging prosthetic feet and ankle components. However, predictability of prosthetic function is excessively affected by altering the prosthetic interface which has a direct effect on the body's ability to convey or mediate receptor input emanating from the prosthesis. All things being equal regarding the fit of the prosthetic socket, altered conveyance of receptor input explains why it is more difficult for a prosthetic wearer to adapt to changes in their prosthetic socket as compared to changes of their ankle and foot components. Our experience has demonstrated that prosthetic manipulation and control is vastly enhanced when augmented by receptor feedback of contact information (contact force and other haptic information) generated between the user and the prosthetic device at the interface location. Emphasis in bio-mechanical and physiological design should therefore include enhanced (sustained) receptor mediation from the residual limb and sensory interpretation at both the perceptual and conceptual level as well as developing feedback to the residual limb from the substitution device, previously referred to in this paper as perceptual contact, and thus produce a system with greater utility in rehabilitation science and medicine. (For an excellent review of perceptual contact theory, refer to the Dudley Childress PhD. paper entitled "Control Strategy for Upper-Limb Prostheses"). (10)

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Theoretical Aspects of Sensory Substitution

For the brain to correctly interpret information from a substitution device, it is not necessary that the information be presented in the same manner or form as the original receptor information system. Thus, it is only necessary to present information from a substitution device in a form of energy that can stimulate receptors at the man-machine (orthotic/prosthetic) interface; for the brain, through the sensorimotor system, to know the origin of the information. This information reaches the perceptual level for analysis and interpretation via the somatosensory pathways and structures. (11) We do not see with our eyes, the optical image does not go beyond the retina where it is turned into patterns of pulses along nerves. Those individual pulses are not any different from the receptor pulses of the big toe. It is the brain that recreates the image or sensation from these identical patterns of pulses. Tactile vision substitute systems (TVSS) deliver optical information to the brain via an array of stimulators in contact with the skin on one or several parts of the body. Optical images picked up by the TVSS camera are transformed into energy (vibratory or direct stimulation) that can be mediated by skin receptors. This "transduced" pulse information is conveyed to the perceptual level of the brain for analysis and interpretation. After training with the TVSS, blind subjects report receiving images in space instead of as stimulation on the skin. They learn to make visual images and visualized perceptual judgments (such as depth) based on cutaneous stimulation when they manipulate their body and camera movement as though they were receiving information from their eyes. (12)

Neuropsychological Mechanism Involved in Sensory Consciousness

Within the skill-based or sensorimotor approach to understanding sensory awareness, sensation is a matter of the "perceiver" knowing that he or she is currently exercising his or her implicit knowledge of the way body actions influence incoming receptor information and sensory processing.(13) Why does seeing provide us with a qualitatively different sensory experience than hearing, taste or touch? Indeed, why does receptor input provoke a sensory experience at all and why does our sensory experience differ in so many respects from other conscious mental phenomenon? The answers to these questions lies in the neuromechanisms involved.

Though knowledge is rapidly accumulating regarding the neuromechanisms involved, sensory consciousness can be explained within the context of sensorimotor function. Implicit knowledge of bodily actions are referred to as "corporality" and is manifest in and measured by the body's response to an interaction between somatosensory and sensorimotor function. An illustration is provided by the sensation of softness one might expect in holding a sponge. Having a sensation of softness consists of being aware that one can exercise certain practical skills with respect to the sponge. One can for example press it, and it will yield under pressure. The anticipated experience or awareness or sensation of softness of the sponge is characterized by a variety of such possible patterns of bodily interactions with the sponge. Thus, the conscious experience of softness is easily characterized by the skill base or sensorimotor approach because it resides in, and is constituted by, the exploratory skill involved. It is impossible to imagine or anticipate what it is like going through all the exploratory patterns of softness while experiencing hardness. When a perceiver knows in an implicit and practical way that at a given moment he is exercising sensorimotor skills associated with softness (or normality), he is then in the process of experiencing softness, becoming aware and conscious of the sensation of softness (or the sensation of normality).

Laws that describe these sensorimotor skills or interactions are referred to as sensorimotor contingencies. These interactions can be explained in terms of corporality and alerting capacity. (14) Corporality is further defined as the extent to which activation of a mediation receptor systematically depends on movement of the body (kinesigenics). The alerting capacity of mediated input is the extent to which the processed input or sensory perception can cause automatic orienting behavior that peremptorily captures the organism's cognitive processing skill (kinetogenics).

Within the context of peripheral constraint ("deafferentation") and compromised sensorimotor function, both corporality and alerting capacity remain an implicit perceptual experience until the perceiver learns to predict or anticipate their mutual and reciprocal interaction, at which time the perceptions become explicit – a fully formulated, developed, conceptual and accurate kinesthetic event. In other words, proprioception is the neural input that signals mechanical displacement of the muscles and joints but this positional input in and of itself does not have an experienced sensory quality (15), a condition similar to the autonomic nervous system. Rather, it is the anticipated effect of extensively processing this neural input and its perceived relationship to alerting capacity that constitutes conceptualization\intellectualization of sensory awareness.

Sensations are never instantaneous, but are always extended over time, and at least potentially, they always involve some form of activity (body movement). Sensation involves the exercising of sensorimotor contingencies: the difference between modalities come from different sensorimotor skills that are exercised.(16) The difference between hearing and seeing amounts to the fact that, among other things, when one is seeing, and when one blinks, there is a change in sensory input. One is hearing if nothing happens when one blinks, but there is a left- right difference when one turns one's head.

It should be possible to obtain a visual experience from auditory or tactile input provided the sensorimotor response is the laws of vision sensorimotor contingency. (17) O'Regan's findings are consistent with Bach-y-Rita's research – sight and sound (as well as sight and touch) can be substituted when a person reacts to acoustical input as though it was coming from their eyes or when a person reacts to optical input as though it was coming from their ears. This requires "skill-based" imagery, or acquired imagery skills commensurate with extensive training. Theoretically, skilled based imagery would be most efficiently maintained or acquired and clinically facilitated by measuring and decreasing the contingent somatosensory/sensorimotor interval, or by measuring (and decreasing) the contingent sensorimotor loop elapsed time. This is not at all an indirect approach because imagery and anticipatory input are inextricably associated – the coinciding presence of one is entirely dependent upon the emerging or established presence of the other.

It should be noted at this time that the interactive association between imagery and anticipatory input can also work in "reverse". If we don't correlate acquired sensory perception skills with an image of normality, then imagery skills or sensations will automatically (by default) correlate with compromised and diminished somesthesia and proprioception characteristic of neuropathic and ablated limbs. This process of reverse correlation seems to occur at essentially the same rate of sensory perception correlation with intact imagery skills. For example, sensory perception correlation with intact imagery skills for trauma related transtibial ablation requires 25 weeks and 34 weeks for disease related transfemoral ablation. Equally significant, once a new motor imagery or "solution" is established (regardless of direction), it's very difficult to change. In the prolonged absence of emerging or established anticipatory input (sensorimotor contingency skills), and in the presence of continuous diminution of somesthesia and proprioception, imagery skills (imaging pseudo sensations) will likewise deteriorate.

"Researchers noticed that when the animals became proficient at the task, the neural patterns involved in the solution stabilized. Stability is one of three major features scientists associated with motor memory – once a motor memory has been consolidated, it can be very difficult to change". (Carmena, J. 2009. (18))

Carmenas's findings are consistent with our clinical experience with neurocorrelagraphy. After the solution or motor imaging period transpires (25-34 weeks post-operatively), it is clinically difficult to reduce previously mentioned contingent sensorimotor loop elapsed time to levels commensurate to and associated with normal imagery skills. In other words, once an individual learns to "view" their body as segmented, separated or amalgamated, it becomes very difficult for them to develop or regain an image of wholeness and normality (and concomitant sensorimotor skills) when connected to and operating a sensory mediation substitution device, such as a prosthesis or orthosis. (It is beyond the scope of this paper to discuss technological implementation and methodology. However, the theoretical implication of sensory substitution and correlation most likely has a profound impact on the inherent nature and efficacious handling of pre and post-operative, preparatory and definitive clinical orthotic and prosthetic protocols. Evidence exists that the immediacy with which a person begins to practice sensorimotor contingency skills is paramount in the overall outcome of orthotic-prosthetic functionality (19, 20), and this immediacy should pertain to both preoperative (if possible) and postoperative neurocorrelation modality training. Proprioceptive neuromuscular facilitation (PNF) in both the affected and contra-lateral limb has been shown in earlier studies to help maintain body imagery and normal sensory perception skills in both the residual and "phantom" limb. (21) The period in which post-operative inflammation and swelling of the residual limb subsides (the primary physiological determinant of preparatory prosthetics) coincides with a period in which the prosthesis is most readily accepted (22) (the primary neuropsychological determinant of preparatory prosthetics) and with the attainment of proficient concentration or imagination of normality and anticipation of contingent sensorimotor function (the primary bio-mechanical/bio-engineering determinant of preparatory orthotics/ prosthetics).

Thus, it is suggested that a sensorimotor skill program can consist of two stages: initially (preoperatively if possible) functional skills can be practiced using PNF neurocorrelation modalities on both the intact and affected limb before the actual preparatory prosthesis (or orthosis) is made available. The second stage coincides with the provision of the preparatory orthosis or prosthesis. At this time, the wearer can engage in practicing with the orthosis or prosthesis under a practice ENP regiment with emphasis on practice repetitiousness, variability, contextual interference and other therapeutic modalities that enhance cognitive processing (23). These cognitive processing modalities (with associated and acceptable neurocorrelation coefficients) should stabilize for a period of three to four weeks and should coincide with and be complimented by appropriate bio-mechanical and physiological clinical intervention modalities, such as dynamic alignment and soft tissue management. All of this should come to full fruition prior to definitive delineation and dispensation).

Until recently, no effort has been undertaken to analyze the laws of sensorimotor contingency related to a mediation substitution device. It is the similarity in the sensorimotor contingency laws that such devices recreate that determine the degree to which users will really feel they are having sensations in the modality being substituted.

To paraphrase, no effort has been made to understand the laws of sensorimotor contingency related to orthotics and prosthetics. It is the similarity of these laws that bio-mechanical engineering and clinical orthotic-prosthetic intervention stratgies recreate that determines the extent to which the user will actually feel sensation in (corresponding to) the orthotic neuropathic limb or the absent limb itself, and ultimately, the extent to which the user will be able to utilize and otherwise benefit from the orthotic-prosthetic device.

The substituted sensory experience associated with an insensate or missing mediation modality is not wired into the neural hardware, but is rather a question of sensorimotor contingencies. (24) The orthosis/prosthesis will function as an effective mediation substitution device only when the bio-mechanical design of the device allows the user to accurately predict or anticipate the changes created in the mediation receptors in response to changing those receptors' position in space; when these perceived changes cause automatic orientating behavior that peremptorily captures furthercognitive processing skills, and when cognitive processing skills include a normal, present and clear imaging of oneself in full view. Thus, having both corporality and alerting capacity, this image of normality should be associated with a sensory experience of strong phenomenal presence. This is indeed the case. Likewise, a mediation substitution device having little corporality and altering capacity will not be associated with an experience of sensory phenomenal presence. (25) If we don't use bio-mechanics to recreate the laws of sensorimotor contingencies, which include predicting or anticipating the effects of strong corporality and alerting capacity, the user will not associate the presence or use of the orthosis or prosthesis with a restorative sense of wholeness and normality.

"One challenge with all microprocessor-controlled prostheses is predictability. With a conventional prosthetic foot, I know exactly what it will do at all times and in all types of terrain and activities. It may not have the range of motion of a human foot, but it is very predictable. All manufacturers will face the challenge of predictability with computer-controlled feet, as the state of technology is not yet able to directly connect the human brain to the control system of the prosthesis". (Johnson, C. 2008). (26)

The control problems mentioned by Johnson are not electromechanical or neurophysiological in nature; they are neuromuscular and neuropsychological and thus bio-mechanical in nature because microprocessor-controlled prostheses (at least in their current state of clinical development) do not necessarily and accurately recreate sensorimotor contingencies; in this case sensorimotor contingencies associated with ankle/foot function. When any type of control system (including microprocessors) is used to substitute or supersede natural neuromuscular control mechanisms, they simultaneously impede neuropsychological control mechanisms. The potential rehabilitation value in mediation substitution (afferent augmentation) and multisensory correlation is most apparent when these modalities are used to assess and determine the optimal relationship between these two control variables, and when that point of balance between each other and equilibrium within themselves is physically measurable. Sensory presence and acquired sensorimotor contingency skills can be accounted for plausibly in terms of physically measurable notions of corporality and alerting capacity. (27) Neurocorrelagraphy helps train the user to acquire "notions" of corporality and alerting capacity while using a mediation substitution device and records this measurable activity for future clinical reference and treatment outcome assessment.

Multisensory Conflict / Proprioceptive Drift.

Fundamental to the idea of corporality is a coherent whole bodied representation rather than an amalgamation of separate body parts. (28) The fundamental sense of corporality (selfhood, selfness, wholeness, normality and egocentric) that is most closely associated with bodily self-consciousness (but not with the cognitive, philosophical, theological or emotional layers of self-consciousness) is experienced as the transparent content of a single, coherent, whole body representation. Less than whole and global ownership of body representations have been referred to as a sense of body part ownership, whereas whole body representation or global ownership are directly associated with the sense of corporality. Multisensory conflict and proprioceptive drift are essentially perceptual illusions (distortions), or misattribution of specific body parts. Vision typically dominates over proprioception and touch. The so called "rubber- hand illusion" (RHI), during which synchronous stroking of a seen and unattached prosthetic hand and one's own unseen hand causes the person to attribute the unattached prosthetic hand to their body (to feel like it is my hand) is an example of misattribution. Several studies have demonstrated that RHI also induces a mislocation of ones' hand toward the prosthetic hand, which is often referred to as proprioceptive drift. As a perceptual illusion, this phenomenon is also aberrant in nature and should not be confused with the idea or sense of corporality; the conscience, conceptual and egocentric awareness of one's whole and entire body. (29)

Optimizing functional Restoration and Physical Rehabilitation

Sensation is conscious when a person is "poised" to cognitively make use of the sensation in their judgments, decisions and rational behavior; that is, when the person has cognitive access to the sensation. (30) An important measure of cognitive access to sensation is anticipation of corporality and alerting capacity. The different types of sensation and their experienced characteristics – their similarities and differences and experienced "phenomenal presence" can all be accounted for in terms of the differences between the sensorimotor contingency skills, and in terms of the way the neural channels are tuned to the environment, namely, by the properties of corporality and alerting capacity. Neural tuning is analogous to exercising properties of corporality and alerting capacity. Exercising properties of corporality and alerting capacity is analogous to sensory consciousness. Having a conscious sensory experience amounts to having cognitive access to sensation. Cognitive access to sensation is used primarily to plan, to rehearse, to choreograph, to resolve, to model, to be poised for, to predict and to otherwise anticipate how the image of our body will be affected by sensory input and how sensory input will be affected by the movement of our body image. In optimizing bio-mechanical and physiological engineering of the P&O device as well as therapeutic intervention with the device, these cognitive processes become so closely associated, so intricately intertwined, so mutually and reciprocally interactive that they become, in effect, indistinguishable. They, in fact, become conceptualized (explicit) neural correlates.

Some authors argue that multisensory correlation is a sufficient condition for self attribution. Others argue for additional cognitive interaction in terms of higher level knowledge of the body. (31) The most compelling argument for higher level involvement has been presented by O'Regan. His arguments are most constraining, and augment the basis of this paper as well as the operational theory of neurocorrelagraphic devices and clinical implementation of neural (multisensory) correlation modalities, such as exteriorized neuropsychogenic proprioception and proprioceptive neuromuscular facilitation. Important aspects of self-consciousness involve additional brain areas in the frontal, multisensory premotor and parietal cortices. (32) If we don't include and involve these volitional areas of the brain for sensorimotor contingencies, multisensory correlation is far less likely to occur and we will be far less conscious or aware of the occurrence. Damasio also agrees with Haggard and O'Regan.(33) These additional areas of the brain, to one extent or another, are inextricably linked to and connected with all aspects of sensory awareness and sensorimotor function; they are linked to and connected by imagination and anticipation

Empathy Training

Understanding and clinical implementation of neural correlation modalities contributes to a more successful outcome of extracorporeal orthotic and prosthetic intervention by facilitating acquisition of contingent sensorimotor skills and by effecting an enhanced sense of wholeness, normality and well being while connected to and operating an O&P device. Consequently, clinical orthotists and prosthetists should be familiar with these concepts and practice them on a routine basis. Walking on prosthetic feet attached to post-acute fracture braces will provide the wearer with a simple and practical demonstration of ENP. When wearing and walking on these braces, familiar somatosensory and sensorimotor function will be compromised (momentarily disrupted) because the wearer is standing on top of articulated prosthetic feet rather than on the ground and because the anatomical ankles are immobilized. This will lead to a precarious, if not impossible, balancing situation (hence a safety belt).

Now let's apply some neuropsychological principles. Instead of concentrating on your feet, concentrate on the floor. In other words, imagine the stimulus experience as no longer coming from your feet, but coming from the floor. It is important not to try to maintain balance by moving your ankles and feet. Instead, completely relax your ankle and feet and concentrate on the floor. Again, imagination is the first critical step in facilitating ENP. Imagine normality, and this image must extend to the floor and include the prosthetic feet. Now while you walk, anticipate what your image of normality is actually doing (kinetic and kinematic activity), and at the same time, anticipate how you will perceive the unique kinesthetic sensory input related to walking in this particular circumstance (natural sensory substitution). Discernible correlation of your image of normality and sensory substitution will begin immediately because your sensorimotor and imagery skills are basically intact. If you indeed had an ablated or neuropathic lower limb, correlation would still take place, but at a slower rate because proprioception and somesthesia have been compromised; the greater the compromise, the greater effort and a longer period of time will be necessary for neurocorrelation to conceptually manifest itself.

It should also be noted at this time the extraordinary bio-mechanical and neuropsychological implications of Osseo-integration in terms of rehabilitation potential. Perceptual contact associated with and characteristic of Osseo-integration has the same immediate and discernible solution or motor imaging effect on the "osseo" trainee that walking on prosthetic feet attached to post acute fracture braces has on the empathy trainee.

"Some patients have reported an improved sense of grounding with the prosthetic foot, improved prosthetic limb control and the perception that the phantom limb is slowly becoming more like the normal limb". (Hagberg, K., Branemark, R. 2009). (34)

Both the osseo and empathy trainee are correlating natural, intact and established musculoskeletal somatosensation and proprioception with imagery, rather than correlating emerging or acquired sensory substitution perception. Therefore, to take full advantage of the rehabilitation potential in Osseo integration, multisensory correlation modalities should be clinically implemented preopertatively (if possible) and immediately post- operative to minimize deterioration of imagery skills. Likewise, passive and involuntary prosthetics (to include non-enactive microprocessor control) should be used judiciously because they inherently impede the body's response to a neuromuscular and neuropsychological voluntary interaction between somatosensory and sensorimotor function.

Clinical implementation and assessment of neural correlation modalities are also helpful in orthotic and prosthetic restoration because they are the most revealing methods of determining whether or not your client is safe when using an O&P device, such as a trans femoral prosthesis. Ask the subject to rehearse or choreograph a finite set of kinesthetic events relating to prosthetic/orthotic utilization, such as walking down a hallway, making a left 180 degree turn, walking back and making another left 180 degree turn and then coming to a standing stop (remember to ask the subject to anticipate everything they will feel and do throughout the entire sequence). After the subject has actually completed this specific and finite sequence, ask if their imitation of sensorimotor skills (reenactment of their rehearsal and choreographic skills) was predictable, consistent and accurate. If the subject reports their imitation skills as being 100% accurate, they can be deemed safe while utilizing the prosthetic/orthotic device for that specific activity. If they report an inaccurate imitation (or any unexpected sensory or motor event or episode during the sequence), the subject is unsafe and should not be allowed to independently continue that particular activity without receiving further training and supervision. Anecdotal assessment of neural correlation (as well as the physical measurement of somatosensory capacity) relating to the safe, effective and efficient operation of the prosthetic or orthotic device will have to suffice until more scientifically relevant and accurate neurocorrelagraphic technologies are introduced into the O&P profession that will allow the rehabilitation specialist to physically measure acquired contingent sensorimotor skills.

Conclusion

In a 2004 lecture, Hugh Herr, PhD, director of biomechatronics at the MIT Media Lab, identified “distributed sensing and intelligence” as a key area for the future of prosthetics research. “Advances in muscle-like actuators, neuroprosthesis, and biommetric control strategies are necessary to increase the merging of body and machine to create an intimacy between the human body and prosthesis. It’s our thesis that such intimacy will create a paradigm shift in this area of rehabilitation. To really push this area of medicine, we need to merge body with machine to create an intimacy between the human body and the prosthetic device”. (35)

This intimacy or personal disconnectedness with the orthotic/prosthetic device is generated when the bio-mechanical design of the device promotes proficient concentration on imagination and anticipation; imagination of normality and anticipation of sensorimotor function. It is the inclusive role of the physical rehabilitation specialist to create, implement and clinically evaluate such a perceptible O&P device. Awareness or sensation of normality appears to be constituted primarily by the expected or anticipated experience of normality; those sensory experiences that are most predictable and coincide with and derived from contingent afferent information bio-mechanically engineered into the mediation substitution device - the essential quality of bio-centrism sensory interpretation in physical rehabilitation science and medicine.

The neurocorrelating effect of this mental visualization or concentration provides physically measurable evidence of acquired sensorimotor skills, normal body imagery skills and normal sensory perception skills. This is relevant and immediately applicable to clinical orthotics and prosthetics because imagery and anticipatory skills of our clients can so easily and rapidly deteriorate and because the recent proliferation of passive and involuntary O&P control systems can diminish or compromise the otherwise favorable outcome of this mental activity, often at the expense of potential in physical rehabilitation.

O&P clinical practitioners and other rehabilitation specialist are encouraged to develop a greater interest in and commitment to bio-mechanical and neuropsychological rehabilitation science and orthotic/prosthetic ancillary physical restoration science to the fullest extent possible. An understanding of mediation substitution, sensory perception and multisensory correlation can provide common ground between clinical orthotics/ prosthetics, bio-mechanical engineering and neuroscience, and forge a pathway for further communication of ideas and exchange of technologies between these otherwise seemingly divergent disciplines. As an aspiring O&P rehabilitation specialist, I believe this same common ground also needs to be established with developmental, clinical and perceptual psychology, and the potential benefit in the interaction of these psychological specialties with bio-mechanical and orthotic-prosthetic and robotics functional restoration and physical rehabilitation science needs to be more thoroughly investigated, and hopefully, adequately understood and appreciated. I strongly believe that greater understanding and appreciation of psychological issues, particularly as they pertain to acquisition and correlation of imagery and sensory perception skills, will enrich all our professional experiences and ultimately provide the greatest benefit to those individuals in need of our concentrated and concerted effort.

In his introduction to a 2002 special issue of the Journal of Head Trauma Rehabilitation focused on neuropsychological technologies, Douglas Chute, PhD, wrote: “The trans-portability of technology should allow the bridging of research protocols to clinical practice. There is no intrinsic reason why the neuropsychologists or rehabilitation specialist cannot fully engage with the new range of neuropsychological technologies appropriate for their patients in rehabilitation”. (36)

The intent of the empathy training section of this paper is to provide the O&P practitioner with a simple and practical method of assisting their clientele in regaining a more complete and personal image and impression of sensory as well as functional restoration without any new technology or additional monetary expenditure.

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Michael received a Bachelor of Science degree in Prosthetics and Orthotics from New York University in 1970, and received certification in Prosthetics in 1972 and Orthotics in 1973. He is a fellow of the American Academy of Orthotics & Prosthetics with 40 years experience as a clinical prosthetist and has been an owner and chief practitioner of an independent prosthetic clinic in the Houston area since 1984. He holds 28 patents in Bio-medical, Mechanical, Extracorporeal Prosthetics and Industrial Art and is the author of the B3P patent application and the ENP Neural Correlation Theory.

"I have utilized pre and post operative neurocorrelation modalities to include both Proprioceptive Neuromuscular Facilitation and Exteriorized Neuropsychogenic Proprioception training starting in 1981 and 1982 respectively with favorable results. I received my initial training in PNF from James Habestro, RPT. during the UTAH ARM course in Salt Lake City in 1980, and have been fascinated with clinical neurocorrelations modalities ever since. Similar to PNF, ENP appears to enhance a more normal body image and normal "phantom" sensation. However, adding the element of neurocorrelagraphic induced activity at the conceptual as well as the perceptual level has the most unexpected engaging and animating effect on the user. There appears to be a relationship between B3P proficiency and the maintenance or attainment of a more natural feeling "phantom limb" and this more natural feeling closely coincides with simultaneous orthotic/prosthetic mechanical function. There also appears to be an inverse relationship between neurocorrelagraphic proficiency and the presence of phantom and/or limb pain. Neurocorrelagraphy also has a direct technical bearing on clinical orthotics/ prosthetics because facilitation of substituted sensory perception is one of the primary biomechanical determinants for the selection and arrangement of socket design, suspension and components. An example would be the combination and alignment of knee and ankle components. Neurocorrelagraphy has wonderful potential in this area because it takes into account all aspects of biomechanical analysis, design and assessment of any particular orthotic/prosthetic design as well as taking into account the resulting acquisition of sensorimotor skills relating to the predictable, consistent and otherwise safe operation of specific orthotic/prosthetic devices. B3P neurocorrelation measurement contributes to a more objective assessment of functional restoration and physical rehabilitation by comparing B3P proficiency (neurocorrelation coefficients) with both the involved and contra-lateral limb. I am very enthusiastic regarding my continued involvement in this area of physical rehabilitation science and the opportunity of working with such marvelous and gifted individuals connected with this area of rehabilitation science. It has been a real treat for me to view clinical orthotics/prosthetics through the eyes of physical therapy, biomedical and electrical engineering and computer science, and I think all HTG research members look forward to having our collaborative effort viewed through the eyes of applied neural and biomechanical engineering science.