Sensory Substitution/Multisensory Correlation in O/P Rehabilitation Science

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Introduction

Rehabilitation science and medicine are coming to realize that extracorporeal orthotics and prosthetics are sensory as well as functional substitution devices, and these substitutions are equally important and mutually beneficial. Researchers have identified a high correlation co-efficient between the presence of normal body imaging and acquired sensory perception skills with 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 allow the visually impaired to "see" with their tongues. Optical images picked up by TVSS cameras are transduced into electrical energy that can be mediated by skin receptors under the tongue, and effectively substitutes the two million optic nerves that normally transmit visual signals from the retina to the brain's primary visual cortex. Michael Merzenich MD. (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. 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. 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 (Although six million bits are transmitted through the optic nerve, 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 it's resources in making constant predictions about one's own body and it's relationship to the environment in anticipation of paltry sensory input reaching it form the outside world. A compelling argument has been made that sensory perception (to include "phantom limb sensation" and motion specific muscular patterns) are related to and result from predictive and anticipatory skills as well as imagery skills.

Medical and prosthetic 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 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 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 elude the amputee. Sensory impressions of and from the substituted sensory modality are relevant to clinical O&P because orthotic-prosthetic control and manipulation skills of the amputee 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 applied loads on and from the O&P device is 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 restoration can be measured by how it effects the fundamental issue of accommodation and facilitation of one's individual and unique capacity for neuromuscular and neuropsychological voluntary interaction with one's environment. Starting as soon as possible in the rehabilitation process, these voluntary control mechanisms should be developed 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 associated sensorimotor skills, body imagery skills and natural substituted sensory perception skills and it's practical application in contemporary orthotic and prosthetic practice.

Applied Neuroscience

We have all asked ourselves why do some of our clients experience so much difficulty, while other clients breeze through, orthotic and prosthetic restoration? All things being equal, the problems are not always directly related to physiology, anatomy, histology, biomechanics or psychology. It is the premise of this paper that some of the problems our clientele experience are often associated with the neuroscience, and particularly, the neuropsychological aspects of O&P restoration. So let's take a closer look at neuropsychology and the potential influence neuropsychology has on 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 and mutually beneficial. Gaining an understanding of how information from natural sensors is integrated into the activation of muscle systems is only part of the bigger picture of sensory substitution, though. Our mental construct that comprises the sense impressions, perceptions and ideas about the dynamic organization of one's own body and its relations to that of other objects, makes up the other.

Sensory Substitution

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 and in the understanding and imitation of motor acts. 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. 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 sensor 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 sensory 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 sensory input with existing knowledge and understanding. The Postcentral Gyrus, within the parietal lobe, is responsible for somatosensation, 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 image 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 Psychogenic Proprioception

The second learning stage of sensory perception, Exteriorization, is of particular interest because it is not only neuropsychological mediation of natural as well as artificial sensory substitution (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 the sensory receptors, particularly those receptors adjacent and nearest to the prosthetic interface, and is then processed and interpreted by the brain. Dycor has developed a machine that, among other things, trains the user to exteriorize sensory perception. The machine is referred to as B3P*, and is a practical biomedical device designed to assist the user imagine what they would like to feel and at the same time, feel what they try to imagine. In the prototype configuration, B3P is designed to facilitate neural (multisensory) correlation in (of) the neuropathic and transtibial lower limb. What we are correlating is imagery and natural sensory substitution, and this correlation is referred to as Exteriorized Psychogenic Proprioception (EPsP), otherwise defined by the ubiquitous term “phantom limb sensation”. The following neural correlation theory has been postulated to explain how B3P and the brain might interact to facilitate EPsP. This theory needs to be scrutinized or otherwise reviewed by individuals interested in and familiar with this and other neuroscience concepts relating to this theory.

EPsP Neural Correlation Theory

EPsP utilizes sensory substitution in much the same way language utilizes words. Words can be interchanged as long as symbolic interpretation of words remain the same. Likewise, sensory input can be substituted as long as the substitution is imagined to be the same. Imagery is the first step in facilitating EPsP and implementing B3P measurement of anticipatory input. The B3P user must imagine normality regardless of his physical state of being and degree of desensitization. Imagination is analogous to symbolic interpretation. Anticipation is the next critical step. B3P trains, measures and records the user’s ability to anticipate specific events, in this case kinesthetic activity (awareness or perception of motion) based on sensory substitution.Correlation is the third critical step. The B3P user learns to associate sensory substitution with the image of normality in such a way not to be expected on the basis of chance alone. EPsP facilitates a mutual and reciprocal relationship between imagination and sensory substitution by anticipating what the image of normality is actually doing and how the correlating sensory substitution will be perceived. The theory of Exteriorized Psychogenic Proprioception is embodied in the previous sentence. Imagination, anticipation and correlation are inextricably linked in EPsP and imagery and sensory substitution cannot be correlated without anticipation.

**History of Neuropsychology*

**B3P is an experimental device and there are no immediate plans for commercialization. Rather, it is the fervent hope of the author that the biomedical profession will infuse into the participating rehabilitation professions existing and appropriate technology. B3P has been registered with the Patent & Trademark Office.*

History of Neuropsychology

P.O. Hebb was apparently the first to use the term nueropsychology in the late 1940's, and the term is used to describe the conveyance of clinical psychology and behavioral 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.

Gaining an understanding of neuropsychology and neuropsychology technologies will help us understand the field of neuroscience as it applies to orthotics and prosthetics. 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.

Origins of Neuropsychology Technologies

Neuropsychology technologies are the result of integrating psychology and biomedical technologies. They are in essence, the science of psychology beginning with the brass instruments of the earliest psychologist and including psychometrics, brain imaging, educational, computational, cognitive science and biomedical 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 played 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, Dycor has developed technologies geared to contemporary orthotic and prosthetic practice and operable within the confines and limitations of existing personal computer capacity. It is the purpose of the empathy training section of this paper to introduce the O&P practitioner to neuropsychology concepts related to the successful outcome of extracorporeal orthotics and prosthetics without any additional technology, but only with the ability to understand neuropsychology principles 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. (2) 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 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.(3)

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 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. (4) 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 function. It may well be the process of anticipation 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 sensors. 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 sensors provide cognitive feedback to the user that more accurately replicates communication with the brain. (5) Using natural sensors 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 disabled population. More importantly, natural sensory communication with the brain is particularly effective when exteriorizing and spatiating sensory perception. The most advanced artificial receptor can process 32 simultaneous signals. In contrast, the fingers of the human hand have an estimated 17,000 touch sensing receptors, or 200-300 touch sensors cm2. With natural sensors, the sensorimotor loop is completed in approximately 70 ms. (6)

Our clinical experience with B3P is somewhat consistent with the findings of Haugland & Sinkjaer. For example, the sensorimotor loop involved in anticipating prosthetic heel contact of the transtibial lower limb is approximately 30ms.

Sensorimotor information regarding spatial relations, orientation and geometric form emanate from the sensory substitution device, and is conveyed (or mediated) by natural sensory receptors, particularly those receptors at the 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 sensory input emanating from the prosthesis. All things being equal regarding the fit of the prosthetic socket, altered conveyance of sensory 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 manipulation (prosthetic control) is vastly enhanced when augmented by sensory feedback of contact information (contact force and other tactile information) between the user and the prosthetic device at the interface location. Emphasis in prosthetic design and clinical implementation should therefore include enhanced sensory mediation from the residual limb and sensory interpretation at the perceptual 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 medicine.

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 sensory 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 (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. (7) 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 pulses of the big toe. It is the brain that recreates the image from these 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 transduced 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 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 the camera movement as though they were receiving information from their eyes.

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 is currently exercising his implicit knowledge of the way his body actions influence incoming sensory information.(8) Why does seeing provide us with qualitatively different sensory experience than hearing, taste or touch? Indeed, why does sensory 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 sensation or awareness 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, then he is in the process of experiencing softness, to be aware and conscious of the sensation of softness.

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. (9) Corporality is further defined as the extent to which activation of a sensory receptor systematically depends on movement of the body. The alerting capacity of sensory input is the extent to which the sensation can cause automatic orienting behavior that peremptorily captures the organism's cognitive processing skill.

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.(10) 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 are the laws of vision sensorimotor contingency.(11) O'Regan's findings are consistent with Bach-y-Rita's research - visual and auditory (as well as visual and tactile) sensory input can be substituted when a person reacts to auditory sensory input as though it was coming from their eyes or when a person reacts to visual 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 will automatically (by default) correlate with compromised and diminished somesthesia 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, imagery skills 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. 2009.12)

*Summary of amputee clients 01/85 thru 06/87, Wilson & Associates P&O Clinic, Houston, Tx. Data prepared for Houston area DRG/TRC contracts.

Carmenas's findings are consistent with our clinical experience with B3P. 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 image 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 substitution device, such as a prosthesis or orthosis. It is beyond the scope of this paper to further discuss clinical implementation and methodology. Suffice to say that 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 prosthetic protocol.

Until recently, no effort has been undertaken to analyze the laws of sensorimotor contingency related to a sensory 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 orthotics and prosthetics recreate that determines the extent to which users will actually feel sensation in (corresponding to) the orthotic neuropathic limb or the prosthesis itself.

Experience associated with a substituted sensory modality (insensate or missing limb) is not wired into the neural hardware, but is rather a question of sensorimotor contingencies. (13) The prosthesis will function as an effective sensory substitution device only when the user can accurately predict or anticipate the changes created in the sensory receptors in response to changing those receptors' position in space; when the sensations cause automatic orientating behavior that peremptorily captures cognitive 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 sensory substitution device having little corporality and altering capacity will not be associated with an experience of phenomenal presence. (14) If we don't use prosthetics 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 prosthesis with restoration 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, 15)

The control problems mentioned by Johnson are not electro- mechanical or neurophysiological in nature, they are neuropsychological because microprocessor-controlled prostheses (at least in their current state of clinical development) do not 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 supercede natural neuromuscular control mechanisms, they simultaneously impede neuropsychological control mechanisms. The potential rehabilitation value in sensory substitution and multisensory correlation is most apparent when these modalities are used to assess and determine the optimal relationship between these two 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. (16) Dycor's B3P machine helps train the user to acquire notions of corporality and alerting capacity while using a sensory 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. (17) 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 illusionary, or mis- attribution of specific body parts. Vision typically dominates over proprioception and touch. (18) 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. This phenomenon is also illusionary in nature, and should not be confused with the concept of corporality; the conscience and egocentric awareness of one's whole and entire body. (19)

Optimizing O&P Restoration/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. (20) 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 “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 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 orthotic and prosthetic restoration, 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 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. (21)The most compelling argument for higher level involvement has been presented by O’Regan. His arguments are most constraining, and form the basis of this paper as well as the operational theory of B3P and clinical implementation of neural (multisensory) correlation modalities, such as exteriorized psychogenic proprioception and proprioceptive neuromuscular facilitation. Important aspects of self-consciousness involve additional brain areas in the frontal, multisensory premotor and parietal cortices. (22) 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. 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 restoration by facilitating acquisition of sensorimotor contingency 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 EPsP. 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 neuropsychology principles. Instead of concentrating on your feet, concentrate on the floor. In other words, imagine 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 EPsP. 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 (kinesthetic activity), and at the same time, anticipate how you will perceive the unique sensory input related to walking in this particular circumstance (natural sensory substitution). Discernable 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 correlation.

It should also be noted at this time the extraordinary neuropsychological implications of osseointegration in terms of rehabilitation potential. Perceptual contact associated with and characteristic of osseointegration has the same immediate and discernable 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, 24)

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 osseointegration, multisensory correlation modalities should be clinically implemented pre (if possible) and immediately post operative to minimize deterioration of imagery skills. Likewise, passive and involuntary prosthetics (to include microprocessor - control) should be used judiciously because they inherently impede the body's response to a 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 transfemoral prosthesis. Ask your client 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 your client to anticipate everything they will feel and do throughout the entire sequence). After your client 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 your client 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), your client is unsafe and should not be allowed to independently continue that particular activity without receiving further training and supervision. Anecdotal assessment of neural correlation skills relating to safe operation of prosthetic and orthotic devices will have to suffice until more reproducible scientific methods are introduced into the O&P profession that will allow the O&P practitioner to physically measure sematosensory capacity and acquired sensorimotor contingency skills.

Conclusion

"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."(Herr, H 2004 23)

I hope this paper will serve the reader well. I hope it reaffirms your interest in and commitment to rehabilitation science and orthotic/prosthetic restoration to the fullest extent possible. My purpose in this presentation has been to provide common ground between the clinical orthotist, prosthetist and neuroscientist, and provide a pathway for further communication of ideas and exchange of technologies between these two professions. Also, my purpose has been to provide the O&P practitioner with a simple and practical method of assisting your clientele in regaining a more complete and personal image and impression of sensory as well as functional restoration.

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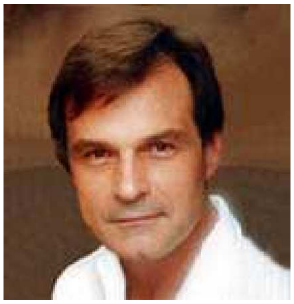

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