University of North Carolina at Chapel Hill
Division of Physical Therapy
DPT Capstone Project

HIIT the Heart, Train the Brain:

Intensely optimizing physical therapy, neuroplasticity, and motor learning to improve poststroke walking recovery - a practical review.

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Background/Statement of Need:

Early in my DPT education, particularly during the second year, I had a difficult time working with patients with impaired motor control. I could identify various motor control deficits/gait impairments to address but was not quite confident in *how* to design interventions and sessions to address them. Gait training complex patients was daunting to me, and many classmates shared similar sentiments.

After my Neuro clinical rotation, I felt things clicked–many ideas and concepts were colored in by experiences in the clinic. I was also able to familiarize myself with the foundational concepts of neurorehabilitation and newer/emerging concepts such as high-intensity gait training, the OPTIMAL theory, and experienced-based neuroplasticity. With mentorship, I was also able to try to incorporate these concepts into my interventions and interactions with patients. This sparked an interest in motor learning and, even deeper, a passion for *motor teaching.*

Over the past year, I have grown a passion for helping people who are in the process of learning how to walk again after a brain injury. I am grateful to have learned from clinical experiences working with people recovering from a stroke, traumatic brain injury, and spinal cord injury. Academically, I was able to be a teacher-scholar for UNC DPT's Motor Control and Motor Learning course and also critically appraise the clinical question *In patients with stroke (P), is high-intensity training (I) more effective compared to low/moderate intensity training and no training (C) for improving ambulatory function (O)?* Now, I hope to pursue a career/specialty in Neuro PT with my top clinical interests including gait training, balance/vestibular rehab, and return to running/sports after acquired brain injury.

I am seeking to address a need by helping current and future UNC DPT students improve their clinical understanding of motor control/motor learning. My hope is that learners will better implement current concepts, evidence, and recommendations to improve walking outcomes during stroke rehab. I hope that through this project and possible integration into the DPT curriculum, other UNC DPT students will be better equipped to confidently and effectively become "movement teachers."

Learning Objectives:

- Learners will summarize key components of motor control theory and motor learning and interpret their relevance in stroke rehabilitation & PT practice.
- Learners will analyze the 10 principles of experience-dependent neuroplasticity and distinguish how to provide optimal experiences for motor learning.
- Learners will outline critical components of the OPTIMAL theory of motor learning and incorporate them in clinical situations.
- Current recommendations for poststroke walking recovery will be presented to be appraised and summarized by learners.
- With a case example provided, students will improve their abilities to effectively implement and illustrate high-intensity gait training in clinical practice.

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HIIT the Heart,  *Train the Brain.*

Introduction: Stroke

A stroke or cerebrovascular attack (CVA) is a neurologic disorder characterized by interrupted blood flow to the brain, typically because of a blockage or rupture.[1] Stroke is one of the largest causes of disability in adults worldwide and the second leading cause of death worldwide.[1,2] A stroke has also been described perhaps more meaningfully as a "brain attack" due to lack of blood flow/oxygen and can cause lasting brain damage, long-term disability, or even death.[2] Hemiplegia/paresis is a characteristic impairment after a stroke, commonly involving weakness and impaired control of movement on one side of the body. Brain damage after stroke can quickly and commonly cause severe sensorimotor, language, and cognitive impairments.

Learning to Walk after Stroke

For people who have survived a stroke, walking - and doing so safely, independently, and efficiently - is a top priority for both improved quality of life and improved overall health outcomes.[1] Walking abnormalities are experienced by ~80% of people after a stroke, with approximately 1 in 4 being unable to achieve independent walking by 3 months poststroke.[1] Learning to walk again is the primary goal of those recovering from a stroke and a major component of rehabilitation.[3]

Moving Forward with the Evidence

As research on neuroscience and human movement has evolved and advanced over the years, so has physical therapy. Many traditional assertions of how humans control movement and their associated approaches for how to optimize recovery have been proven to be limited, less effective, or just plain wrong. There have been major shifts away from previous theories of motor control such as hierarchical or closed-loop theories towards other explanations of skilled movement and recovery such as the Dynamic Systems Theory and neuroplasticity.[4-5]

In 2021, The Academy of Neurologic Physical Therapy (ANPT) published a position paper urging clinicians to "move forward" and embrace emerging research and theory regarding neurorehabilitation and walking recovery.[4] Some of the fundamental theories underlying traditional neurofacilitation approaches such as the Bobath Method, neurodevelopment treatment (NDT), & proprioceptive neuromuscular facilitation (PNF) have been tested, studied, and found to be less effective compared to other interventions for walking recovery.[4,6] For example, we now know that handling for/facilitating "perfect" walking is unnecessary to achieve optimal recovery and allowing variability even to the point of introducing error/difficulty can enhance learning to walk after a stroke.[4,7] We have also learned that we can "leap-frog" over interventions focusing on static balance/postural control to provide mobility training at higher intensities, even for those with severe impairments.[4]

This review examines theories underlying current concepts and recommendations for neurorehabilitation (such as neuroplasticity, motor control/learning, OPTIMAL Theory, task-specific training, and high-intensity gait training) and seeks to incorporate them practically into effective physical therapy interventions to improve walking for people recovering from stroke.

Movement Theory: The Guide to Effective Movement Practice

Drs. Richard Schmidt and Carolee Winstein describe motor control and motor learning as the "software" that controls the "hardware" (muscles, bones, nerves) for purposeful human movement.[11] Motor control is defined as "the process of initiating, directing, and grading purposeful voluntary movement".[8] In many cases, stroke survivors need to address various "software" AND "hardware" problems during practice and recovery to control their movement in functional ways. *Studying and understanding how movement is controlled (theory) is key to improving disordered movement (practice).*

Traditional Theories of Motor Control

Traditional theories of motor control are highly focused on a "top-down" approach, stating that the brain/CNS is strictly responsible for programming the voluntary movement of the body.[9] These theories have traditionally guided practice but rely on assumptions that the brain possesses unrealistic levels of computational power and storage capacity to process instantaneously & program every movement. Below is a chart further detailing traditional theories, their effects on PT practice, and their major limitations.[9]

Theory:	**Premise:**	**Clinical Implications:**	**Limitations**
Reflex Theory (Sherrington, 1906)	- **Reflexes are the basis for movement** - Reflexes are combined into actions that create behavior. - Movement is controlled by stimulus-response.	- Stimulate good reflexes - Inhibit undesirable (primitive) reflexes - Rely heavily on feedback **- Use sensory input to control motor output**	Does not explain spontaneous, novel, or voluntary movement (all can occur without input)
Hierarchical Theories (Adams, 1971)	- **Cortical centers control movement in a top-down manner.** Reflexive movements dominate only after CNS damage. -Closed-loop Mode: Sensory feedback is needed and used to control movement. - Voluntary movements are initiated by "Will" (higher levels).	- Identify & prevent primitive reflexes - Reduce hyperactive stretch - Normalize tone - Facilitate "normal" movement patterns, and discourage abnormal movement patterns **- Decreased variability is the goal**	Does not explain bottom-up control, the effects of movement context, or the development of lower level control before higher development
Motor Program Theory; Schema Theory (Schmidt, 1976)	- Adaptive, flexible **motor programs (MPs) and generalized motor programs (GMPs) exist to control actions** that have common characteristics. - Open Loop motor control: rapid movements without peripheral feedback. - Schema = Generalized rules (spatial and temporal) that generate muscle patterns to produce a specified movement	- Abnormal Movement includes abnormalities in central pattern generators or higher-level motor programs. - Improve storage of rules for force and timing with repeated practice - Retrain movements important to functional task **The goal is storing/refining rules for motor programs**	Does not explain novel movements and does not account for the effects of the environment. Storage Problem: cannot have one motor program for each possible movement.

Bernstein: The Father of Dynamic Systems

The work of Russian neurophysiologist Nikolai Bernstein is often cited as a starting point for modern theories of motor control and learning. He suggested that the body is a complex mechanical system with many parts (coined *"degrees of freedom"*) that must be controlled to perform any movement task.[10] He famously theorized how *variability* is an important aspect of motor control: even experienced blacksmiths use a variety of hammer trajectories yet consistently hit the anvil in the right place.[10]

Bernstein was one of the first to understand movement as a complex interaction between the nervous system and the sensory environment–an interaction that requires coordination & control of many degrees of freedom to complete movement tasks. Bernstein described movement practice as "repetition without repetition", where one actively repeats the *solving* of a motor problem rather than repeating a single movement over and over.[10]

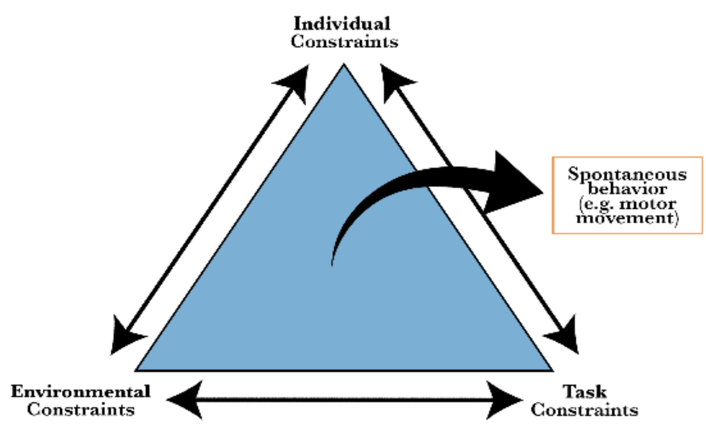
One Motor Controller vs. Dynamic Movement Systems

Other researchers expanded Bernstein's concepts in their study of human motor control and learning. Current theories are now heavily *systems-based* and integrate how factors such as the individual, the environment, and the nature of the task at hand can affect *motor control from the "bottom-up"*.[9] Current theories suggest that movement is the result of *dynamic systems*.[9] The body is composed of multi-leveled, complex systems (nervous, sensory, musculoskeletal, cardiovascular, respiratory, endocrine, etc.) that change, organize, and interact with other systems to skillfully complete movement tasks. The premise that multiple interacting systems affect movement is known as *multi-causality*. In dynamic systems theory, movement is attributed to a multi-causal process between multilevel elements/systems, not just a single system or movement "controller".

Self-Organization/Soft Assembly of Systems for Motor Control

Motor control is described as a self-organizing process where *movement & spontaneous behavior emerges based on specific demands of dynamic systems (rather than being programmed by higher centers).*[9]

Newell (1986) expounds on this, stating that goal-directed movement emerges according to specific constraints of the person, task, and environment (see figure; right).[11] Newell also suggested that *perception* (understanding/applying meaning to input) is more important than sensation for action.[11] Elements of movement are *softly assembled* from our dynamic systems as each motor action self-organizes within a specific context.[9]



Another way to help describe the self-organizational aspect of dynamic systems is through the analogy of a beehive. In a beehive, there is no single bee that simultaneously does all the jobs or programs the actions of all other bees (build a hive, make honey, raise baby bees, fight off predators, etc). Instead, each bee works together with other bees to complete necessary tasks and functions for the hive. The drones mate with the queen to lay eggs, while the other bees work together to build/repair the honeycomb, clean & care for the hive, forage nectar, and raise new workers.

Collectively, the bees *self-organize* according to the specific demands of the context to function as a thriving hive.

An Integrated Dynamic Systems Approach to Rehabilitation

To move purposefully, humans use many different systems that can self-organize and adapt. A dynamic systems approach emphasizes the role of *all systems* in motor control and neurorehabilitation rather than just the brain and spinal cord in isolation. *This approach strongly promotes exploration, problem-solving, and practice of functional tasks.* Treating patients from a dynamic systems approach may not rely as much on telling them how to move or repeating the perfect movement. Rather, a dynamic systems approach calls for clinicians to *create the right conditions for learning and get out of the way*.

Components of an Integrated Systems-Based Theory of Motor Control.[9]

Theory:	Premise:	Clinical Implications:
Dynamical Systems Theory (Bernstein, 1967; Turvey, 1977; Kelso & Tuller, 1984; Thelen, 1987)	**- Movement emerges to control degrees of freedom.** - Patterns of movements self-organize within the characteristics of environmental conditions and the existing body systems of the individual. - Functional synergies are developed naturally through practice and experience and help solve the problem of coordinating multiple muscles and joint movements at once.	- Movements are self-initiated - Help gather information about possibilities and adaptations for movement - Errors are expected AND allowed for learning to occur **- An increase in variability in movement is desired and encouraged**
Ecological Theories (Newell, 1986; Gibson & Pick, 2000)	**- The person, the task, and the environment interact to influence motor learning.** - The interaction of the person with any given environment provides perceptual information used to control movement. - The motivation to solve problems facilitates learning.	- Perception > Sensation - Help patient explore multiple ways to achieve functional task → Discovering the best solution **- Consider the interaction of the person, environment, and task**
Systems Model (Shumway-Cook, 2007)	**- Goal-directed Behavior is Task Orientated** - Multiple body systems overlap to activate synergies for the production of movements that are organized around functional goals.	- Practice tasks under a variety of conditions & environments **- Use identifiable, goal-directed, functional tasks**

Task-Specific, Goal-Directed Training: Repetition without Repetition

Evidence shows that task-based training is superior to impairment-based training for walking recovery after a stroke.[1] A sign of learning/skill mastery is *variability* - being able to complete a movement task in various ways and across different environments. *As learners practice reaching their goals and gain more movement experience (repetition without repetition), they can develop multiple complex solutions to the same problem and adapt to perform them with speed and efficiency.*

Recommendations for task-specific training state that it should be: goal-directed, relevant to the patient and the context, repetitive (involving massed practice of the task), aimed towards the reconstruction of a whole task, and reinforced with positive and timely feedback.[1,12] *When possible, clinicians shouldn't direct patients to merely repeat movements - training should involve practicing specific tasks, with a specific goal in mind.*

Motor Learning: How Humans Gain Motor Control

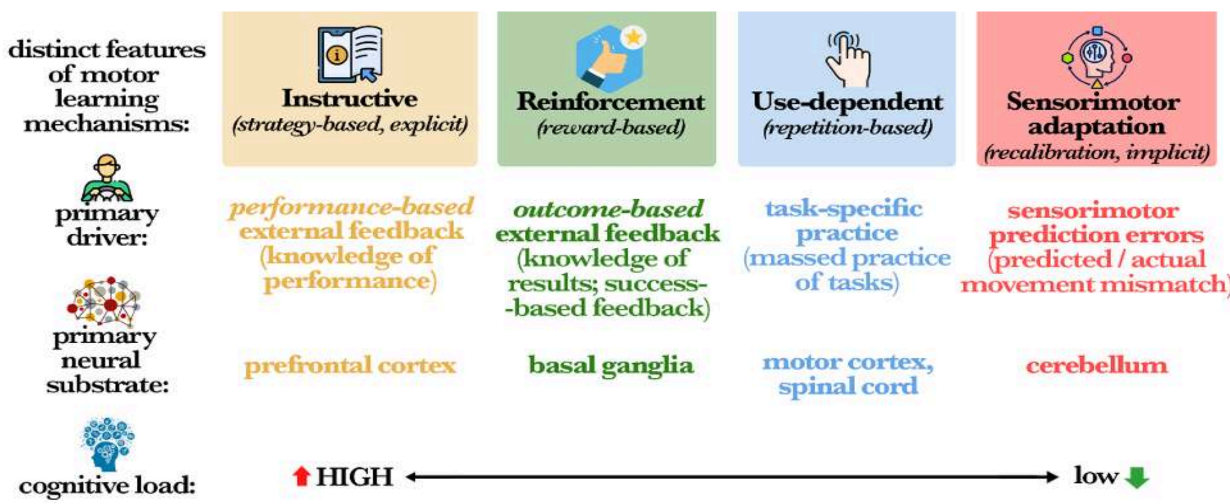
Motor learning is defined as "a set of processes associated with practice or experience leading to a relatively permanent change in the capability for movement".[8,14-15] Learning (& re-learning) of functional movements is one of the most fundamental goals of neurorehabilitation and is now a major field of research and a standard part of entry-level DPT education. Major factors affecting motor learning have been studied with specific types of practice, feedback, instruction, and motivation identified as "therapeutic ingredients" that facilitate effective neurorehabilitation.[14-16]

"Currently, learning is our best hope to remodel the damaged brain".[13]

Recovery/re-learning of walking occurs through adaptation (reacquisition of movement patterns) and through compensation (use of alternative movements to achieve the same goal). Adaptation and compensation both respond to rehabilitation/practice, and both require some aspect of learning.[8] Learning is "the acquisition of knowledge or skills through experience, study, or by being taught".[8] It is a key mechanism of walking recovery and a major focus of rehabilitation after a stroke.

Mechanisms of Motor Learning

There are 4 well-studied mechanisms of human motor learning (use-dependent, instructive, reinforcement, and sensorimotor adaptation-based); each with its own specific behavioral drivers and distinct neural substrates.[14] Mechanisms of motor learning can occur in parallel to enhance motor learning as therapists skillfully incorporate drivers of learning into movement practice.[14-15] The following figures describe the mechanisms and associated neural substrates in more detail.[14]

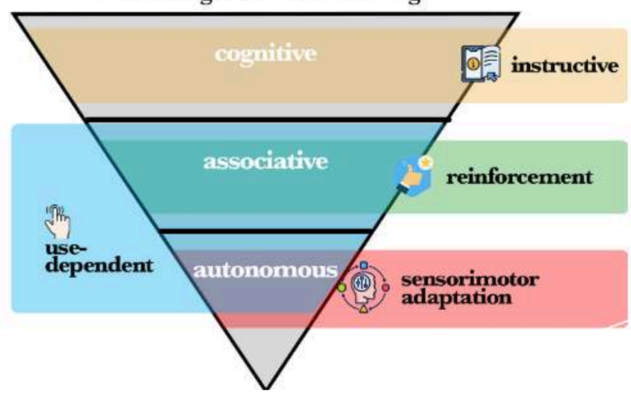


Stages of Learning

Bernstein proposed that the ability to control many degrees of freedom is a key component of motor control and a sign of learning a new skill. In Bernstein's 3-stage model, the individual simplifies their movement by reducing the degrees of freedom in the initial stage. In the advanced stage, they gain control over a few more degrees of freedom to complete a task. Finally, *in the expert stage, the learner possesses control over all the degrees of freedom needed to carry out the task in a coordinated fashion*.[8,9-11]

Gentile proposed two stages of learning with a taxonomy for progressing tasks and activities.[17] The first stage is focused on *understanding the purpose of the task*: interpreting relevant environmental information and developing movement strategies appropriate for completing the task.[17] The second stage is focused on *diversifying and redefining movement*: adapting movement to changes in the task and environment and being able to perform the task consistently and efficiently.[17]

Lastly, *Fitts & Posner* proposed three stages of learning that have been largely adopted today (See Inverted Triangle; R).[8,14-15] They outline 1) a *cognitive stage* where movement is slow and requires thought, 2) an *associative stage* where movement becomes more fluid, and finally 3) an *autonomous stage* where movement is accurate, consistent, and efficient - with much less cognitive activity required.[8] Various mechanisms of motor learning contribute to learning during each stage.[14]

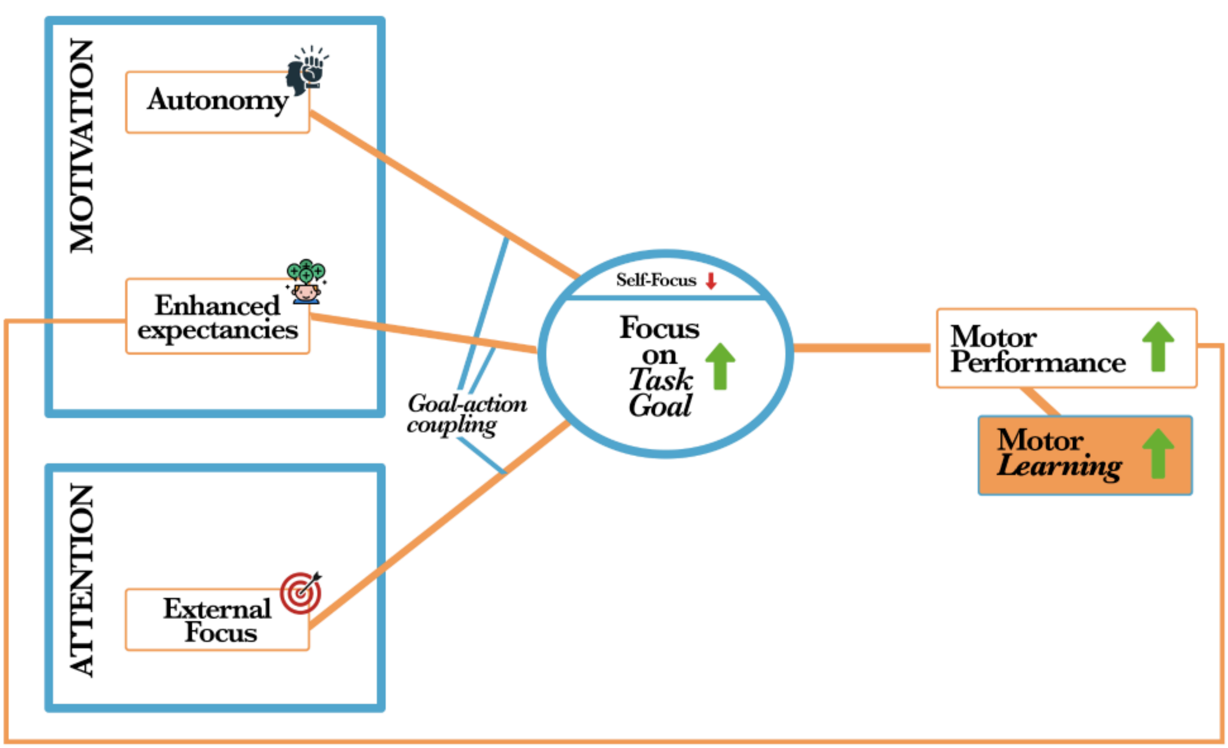


The OPTIMAL Theory of Motor Learning.[18]

The OPTIMAL Theory examines social, cognitive, affective, and motor behavior-–how motivation and attention influence motor learning.[18] It states that *increasing the focus on the goal of a specific task (rather than on self) results in increases in motor performance and motor learning*.[18] There is ample evidence supporting 3 critical factors of OPTIMAL learning: autonomy, enhanced expectations, and external focus of attention.[18] Increased self-focus can cause decreases in performance and learning, resulting in a vicious cycle, whereas *increased focus on the task goal results in motor performance gains, enhanced expectations, and a virtuous cycle of motor learning*.[18]

Conceptual Framework: The OPTIMAL Theory.

Wulf G, Lewthwaite R. Optimizing performance through intrinsic motivation and attention for learning: The OPTIMAL theory of motor learning. 2016



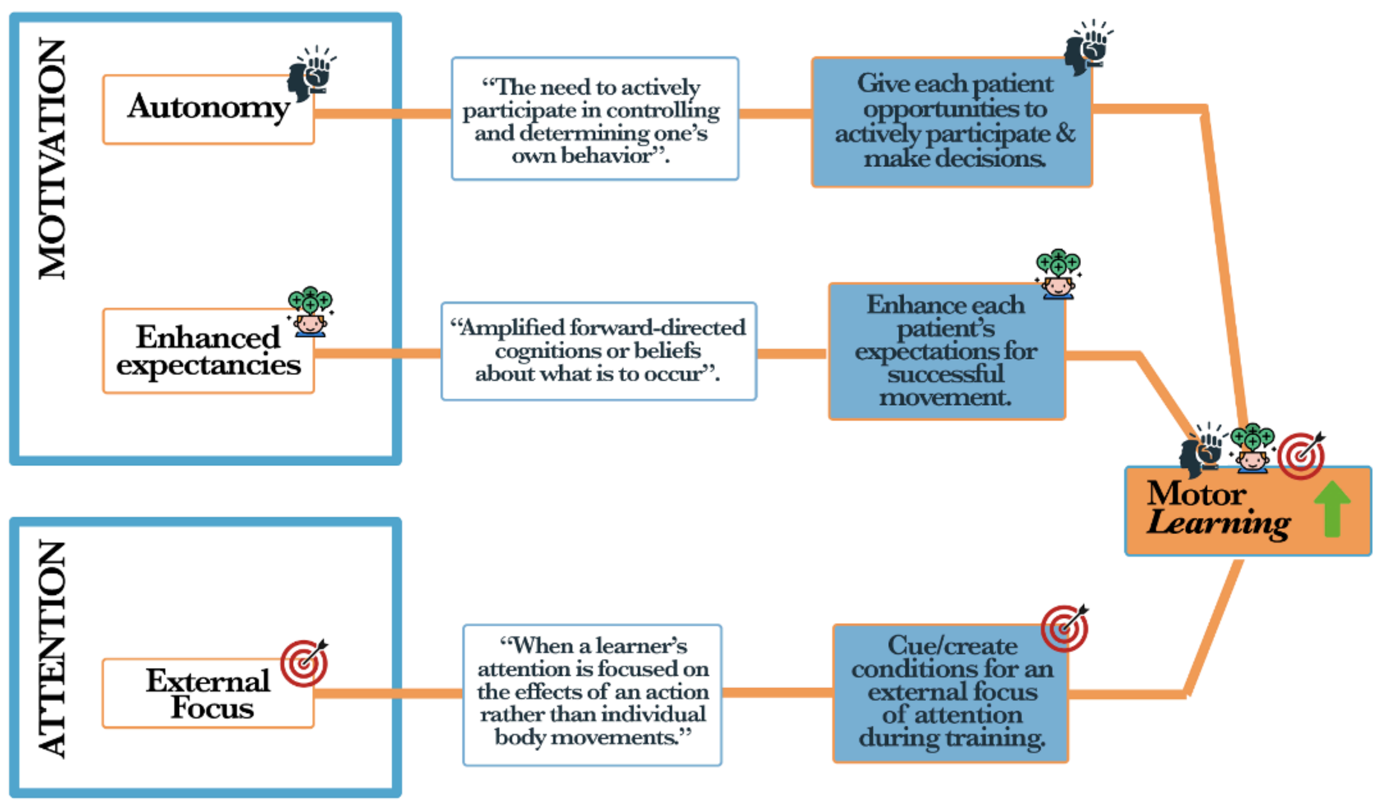
OPTIMAL Learning Requires OPTIMAL Teaching

If exercise and functional training are the "meat and potatoes" of physical therapy, then perhaps they need to be seasoned with the spices of motor learning to be most tasteful. *An understanding of OPTIMAL theory implies that simple, evidence-based changes in instruction, communication, & feedback will enhance how effectively a patient learns.* Here are the three critical components of OPTIMAL Learning and their proposed mechanisms:

- Autonomy allows the patient to satisfy a basic psychological need by exercising control over/affecting their environment, resulting in superior learning and task performance.[18-20]
- Enhanced expectancies promote self-efficacy through positive feedback, normative feedback, and changing the patient's perception of task difficulty & their definition of success.[21]
- An external focus of attention increases goal-action coupling, promotes implicit learning, and leads to greater automaticity in movement control.[18,22] Evidence strongly suggests that an external focus results in better outcomes for motor learning, however, research shows that most clinicians still provide cueing for an intrinsic focus of attention when instructing patients.[22]

The following graphic further defines the critical components of OPTIMAL Theory & summarizes how they can be skillfully incorporated into clinical practice & interventions.[17]

Conceptual Framework: Incorporating The OPTIMAL Theory into Clinical Practice.
Wulf G, Lewthwaite R. Optimizing performance through intrinsic motivation and attention for learning: The OPTIMAL theory of motor learning. 2016



Listed below are some practical examples to spice up clinical practice by promoting autonomy support, enhancing expectations for successful movement, and promoting an external focus during training.

Using patient-led goals and predictions incorporates all 3 critical components of OPTIMAL Theory, resulting in a motor learning triple threat.[18]

Practical Examples of Critical Components of OPTIMAL Theory in Practice

Autonomy Support:	**External Focus of Attention:**	**Enhanced Expectancies:**
Promote self-efficacy; empower patients to believe in own abilities & make decisions	Provide cueing that promotes a focus on a desired effect or goal	Tell individuals that they will perform well (yes, it can be that simple)!
Allow patients to choose the order in which they will perform interventions	Refrain from cueing that promotes a focus on self or moving a body part	Provide feedback after successful trials rather than unsuccessful trials
Choose activities that align with the patient's interests and hobbies	Use analogy when providing instructions and cueing movements	Provide positive, normative, & peer-group performance feedback
Give patients a choice over progressions and regressions of task difficulty	Manipulate task/environment to facilitate an external focus	Set attainable goals & realistic definitions of success
Utilize a "coach" approach to support & facilitate behavior change.	Use knowledge of results to direct focus on desired effects and movement goals	Collaborate for positive re-framing to remind that learning is possible
Ask patients to set meaningful goals and predictions for their movement	*Motivate the patient to focus on meeting goals/surpassing predictions during tasks*	*Bolster expectations of future success toward patient led predictions/goals*

Neuroplasticity - the Underlying Process of Learning

Traditional beliefs in neurorehabilitation implied that brain structure/function was fixed and resistant to change. Outside of development, adults had what they had, and once brain damage occurred, it was permanent. Improvements after brain damage occurred through compensation only. Thankfully, now there is mounting evidence that *the brain is constantly adapting and learning*–even, *especially after a brain injury*.[13,23-24]

Neuroplasticity describes the incredible way that we grow, develop, and adapt. It is the basis of all learning and behavioral change! Clinically, it is the underlying process for a patient to recover from an injury and to re-learn and master any belief, function, or movement. *Providing patients with the necessary experiences to induce neuroplasticity is a fundamental approach to learning to walk again - it is how we remodel the damaged brain*.[13]

What is Neuroplasticity?

Neuroplasticity is defined as *"the ability of the central nervous system to change its activity in response to intrinsic or extrinsic stimuli by reorganizing its structure, functions, or connections"*.[24] In simpler terms, "neuro" means related to the brain/nervous system, and "plasticity" means the quality of being easily shaped or molded. Both spontaneous and therapy-induced mechanisms of functional recovery have been studied after brain injury and neuroplastic changes have been found that support sensory, motor, language, and cognitive improvements.[23]

Experience-Based Neural Plasticity: Neurons that fire together, wire together

The frequency, type, and intensity of experiences during rehabilitation guide structural and functional changes, with plasticity being driven through repeated experiences of movements/behaviors.[23-26] Experience-based neural plasticity mainly occurs through synapses between neurons that strengthen, weaken, and rewire.[13] The "neural garden" is ever-changing as we experience life, with constant pruning/deletion of old connections and growing of new connections.[13] *Through intentional practice and repetition, the neurons that fire together wire together to learn & master new movements.*

"We Talkin' 'Bout Practice?" - Allen Iverson (- Michael Scott) (- Ted Lasso)

Practice (performing a skill/activity repeatedly or regularly to improve or maintain one's proficiency) is *one of the most influential drivers of experience-based plasticity*. Three main patterns of plasticity have been identified in response to practice: *1) Reorganization of Activation, 2) Decreased Activation, and* last but certainly not least, *3) Increased Activation.*[27]

There are two different practice-related reorganization of activations*: redistribution* of activations and *functional reorganization* of activations. In redistribution, the areas for functional activation remain the same, however *the levels of activation change with practice.* In functional reorganization, *different brain regions are engaged* as processes "switch" to perform specific functions and tasks. These patterns are often seen because of compensation for damaged brain regions and lost functions.[27]

A pattern of *decreased activation* is seen with the practice of higher cognitive tasks and working memory, and reflects increased efficiency in the response of neural networks to hasten reaction/processing time.[27] In contrast, a pattern of *increased activation with* *practice is typically related to the repetition of motor or sensory tasks.* With the practice of motor tasks, increased activation results from long-term potentiation ("LTP"; a persistent increase in synaptic strength in response to high-frequency stimulation of the synapse) and increases in horizontal connectivity with the primary motor cortex (M1).[27]

Blazing Trails

Imagine walking through a forest. If no one has ever walked there, there isn't much of a trail to follow, and movement is difficult. You might have to remove some tree branches or do some bushwhacking. But with repeated walking down a specific trail, the path becomes more clear and requires less thought and energy to navigate. With enough repetition, the path gets clearer and broader, and a permanent trail forms between the starting point and the destination.

Just as walking the same specific trail over and over creates specific changes over time, practice results in specific neuroplastic changes as connections strengthen and rewire in the brain.[27] As a clear path is formed and experience is gained, walkers can use it to walk faster, further, and more efficiently. Neuroplasticity subserves motor learning, but requires us to repeat specific functions to make improvements and lasting adaptations.[26] Some state that "practice makes permanent", but perhaps philosopher Henry David Thoreau described the impact of specific repetition most Thoreau-ly:

***"**As a single footstep will not make a path on the earth, so a single thought will not make a pathway in the mind. To make a deep physical path, we walk again and again. To make a deep mental path, we must think over and over the kind of thoughts we wish to dominate our lives."*

- Henry David Thoreau

<u>Neuroplasticity in Practice: Remodeling the Damaged Brain</u>

Kleim & Jones (2008) identified 10 principles of experienced-based neural plasticity that apply to rehabilitation after a brain injury. Important "active ingredients" of task practice including *specificity, repetition, salience, transference, and intensity* were identified as variables that directly impact neuroplasticity and recovery after brain injury.[13,24-26] Other variables that impact PT intervention include the *age of the patient and the stage of the condition:* evidence has found that younger patients show larger functional changes during recovery and that there is a *critical time window* where the most neuroplasticity occurs within the first 3-6 months after a stroke.[13,23,28]

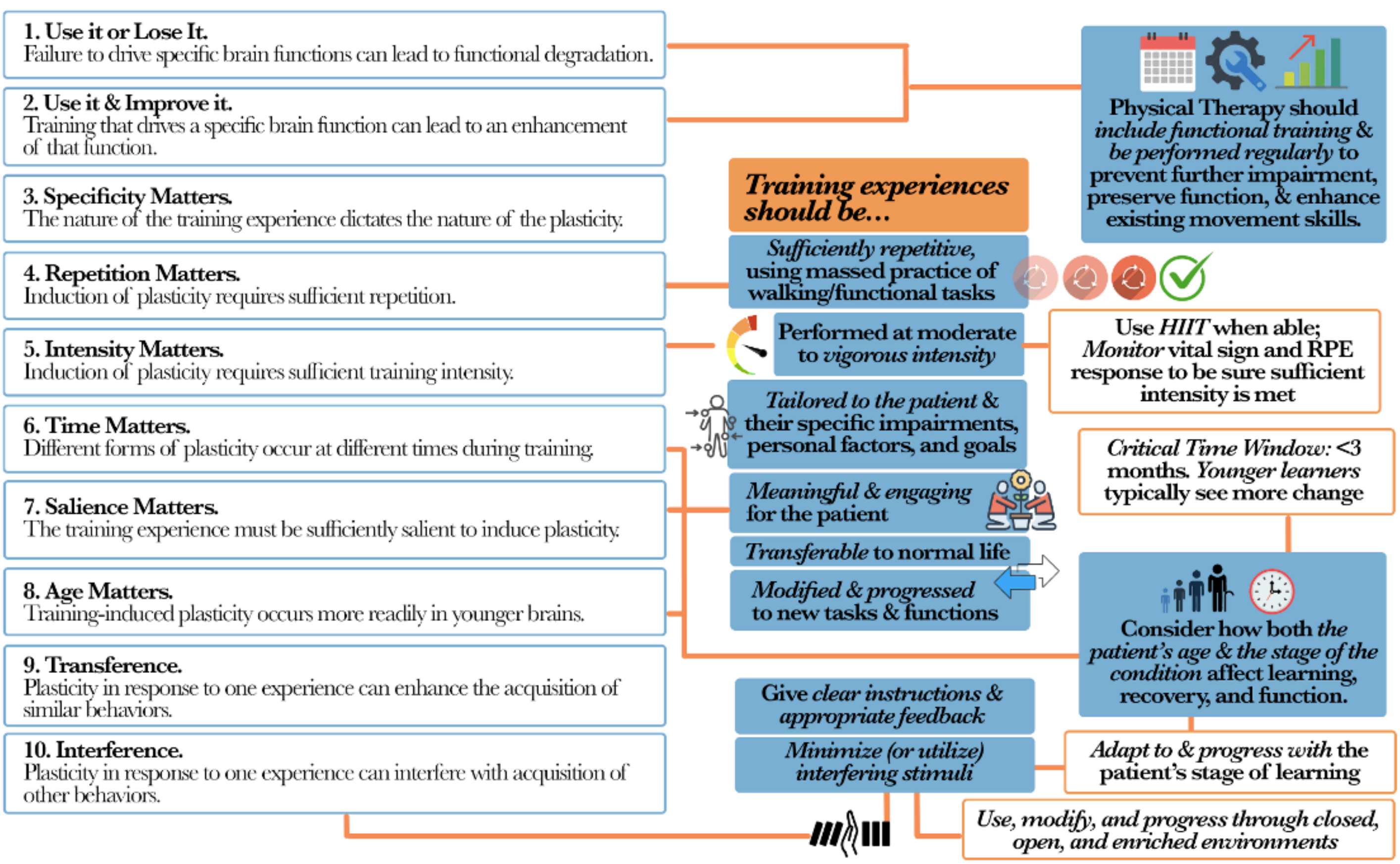
Major principles of neuroplasticity guide clinicians to practice specific tasks with active ingredients that are sufficiently repetitive, intense, and specific for each patient to maximize functional change. They remind us to meet patients where they are and to provide meaningful experiences to help them recover and adapt.

Bridging Theory and Practice

Many variables have been found that impact motor learning and neuroplasticity after brain injury. Clinicians can create an environment that facilitates learning and use specific tasks in that environment to provide optimal practice experiences to enhance neuroplasticity. The following framework further describes key principles of experienced-based neuroplasticity and associated recommendations for practice.

Conceptual Framework: Incorporating Principles of Neuroplasticity into Clinical Practice.

Kleim JA, Jones TA. Principles of experience-dependent neural plasticity: implications for rehabilitation after brain damage. *J Speech Lang Hear Res.* 2008



As neuroplasticity is studied more, it offers guidance to help clinicians intervene in a way that maximizes functional change and recovery during practice.

Studying the process of neuroplasticity also offers us hope: *the damaged brain can repair & remodel itself. And as we walk alongside patients during recovery, they are rewiring their brains to learn how to move again.*

Current Recommendations for Poststroke Walking Recovery

There is firm agreement in the US, UK, Canada, and Australia & New Zealand recommending a task-oriented practice of walking or components of walking to improve function after stroke.[1,29-31] The chart below summarizes the current consensus items that are recommended by various international guidelines.

Strongly Recommended Items for Poststroke Walking Recovery:[1,29-31]

Intervention:	Recommendations:	Methods:	Measures:
Task-oriented practice of walking (or components of walking)	- Practice should be tailored to the patient's specific needs and goals - Practice should be repetitive in nature	- Overground Walking - Treadmill training* - Circuit-training* - Endurance training* *as adjuncts to overground walking training	- 10-meter walk test - 6-minute walk test - Functional Gait Assessment (FGA)

In the US, the ANPT has developed clinical practice guidelines for improving walking function for those >6 months after stroke/CNS injury (chronic stage).[32] Walking training at a moderate-high intensity and virtual reality (VR) walking training are strongly recommended. Moderate and weak recommendations include strength training, cycling/recumbent stepping, and balance training with VR or augmented visual feedback.[1,32] The guidelines *do not* recommend body-weight-supported treadmill training or robotic-assisted walking training when compared to an active approach that supports motor learning. They also state that clinicians should not use static standing/sitting balance training to improve functional mobility compared to active interventions.[32]

Emerging interventions for walking recovery include high-velocity strength training of propulsion-generating muscles, the use of virtual/augmented reality systems to enrich training environments and enhance motivation/feedback delivery, and *high-intensity interval training*.[1,32-35]

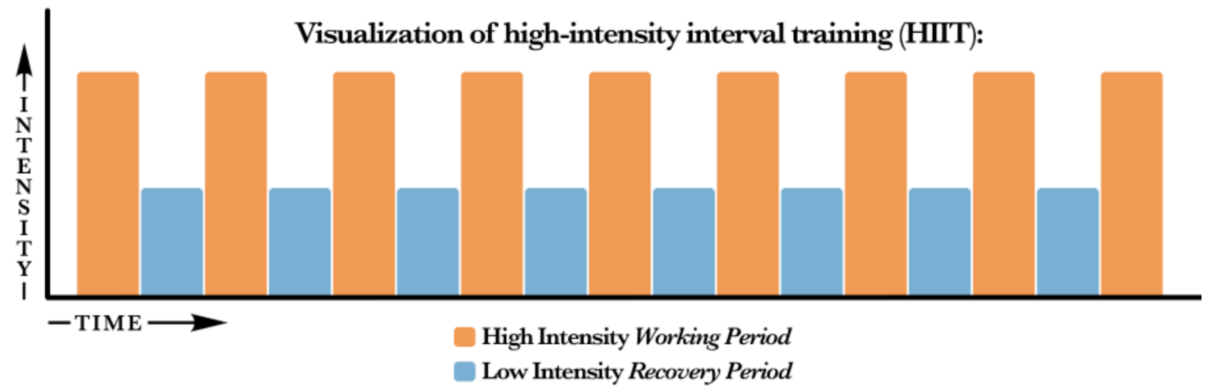
High-intensity interval training (HIIT): An Emerging Intervention for Walking Recovery

The Scottish Captain Robert Barclay recorded one of the earliest examples of interval training in 1813, when he separated his famous long walks with ½ mile runs.[36] Since then, interval training has been incorporated into athletic training and even evolved to include scientific high-intensity protocols used by Olympic distance runners throughout the twentieth century.[36] It was not until about twenty years ago however that research began to look into the benefits of interval training in clinical settings.[37]

Traditional physical activity/exercise guidelines after stroke recommend moderate-intensity continuous exercise (MICE) to improve fitness and walking outcomes.[38] Recently, high-intensity interval training (HIIT) has emerged as a promising strategy for improving both walking capacity and walking performance after stroke.[1] HIIT is more time-efficient than MICE and has been shown to promote similar if not superior improvements in cardiorespiratory fitness when compared to MICE.[36] HIIT is also more engaging (less continuous and more intense) than MICE, which may promote adherence and motivation. Additionally, higher intensities of exercise have been found to positively affect the induction of neural plasticity after a brain injury.[1,13] The ANPT emphatically states that *Intensity Matters* and is campaigning for high-intensity gait training to be implemented more comprehensively into clinical practice.[4,32]

What is HIIT?

High-intensity interval training is classified by periods of high exertion/intensity separated by recovery intervals of either low-intensity exercise or complete rest.[36] HIIT can take on various modes of delivery depending on the goal; walking, running, cycling, rowing, and strength training are all common activities that can be performed in high-intensity intervals. See below for a reference visualization of HIIT.



Indicators of Intensity

There are two primary indicators by which the intensity of exercise or training is defined and measured: *heart rate (HR) response and perceived exertion.*

Increased intensity of exercise stimulates increased heart rate responses as the cardiorespiratory system works to pump blood and supply oxygen to be used by skeletal muscles during exercise. HR is commonly measured as beats per minute. The most common measures of intensity are the % of maximum HR (HRmax) and the % of total heart rate reserve (HRR; calculated by *HRmax - Resting HR*) being used.[39-40]

To find an individual's age-predicted HRmax, the following formula is used: *HRmax = 207 - (age x 0.7).*[40] Target heart rate training zones (based on %'s of HRmax) have been identified and delineated based on exercise intensity, energy system, and perceived exertion. These zones are used as targets to reach desired intensities during exercise. The following chart distinguishes the various HR training zones.

Heart Rate Training Zones:

ZONE	% of HRmax	Intensity	Energy System
ZONE 1	50-59%	Very Light	
ZONE 2	60-69%	Light	
ZONE 3	70-79%	Moderate	Aerobic
ZONE 4	80-89%	Hard	Anaerobic & Aerobic
ZONE 5	90-100%	Maximum	Anaerobic

Perceived exertion (how hard one feels they are working) is another way to gauge the intensity of exercise. It is more subjective than heart rate response and also may not always correlate with heart rate.

The Borg Rating of Perceived Exertion (RPE) scale is the most commonly used measure of perceived exertion.[41] It ranges from 6 being the lowest effort (rest) to 20 being the maximum effort. It is designed to reflect normal heart rate ranges/responses - if you multiply the Borg rating by 10 then that is the estimate of heart rate based on perceived exertion (based on RHR: 60 and HRmax: 200). The Modified Borg scale ranges from 0 to 10. This is more intuitive and easier for patients to understand, however, it is less specific and does not correlate with HR response as linearly. See the chart (right) for a more detailed description of the Borg and modified Borg RPE scales.[41]

Borg RPE Scale:	Modified Borg Scale:
6 - at rest 7- very, very, light 8 - 9 - very light 10 - 11 - fairly light	0 - at rest 1 - very easy 2- somewhat easy - 3- moderate
12 - 13 - somewhat hard 14 - 15 - hard	4 - somewhat hard 5 - hard 6 -
16 - 17 - very hard 18 - 19 - very, very, hard 20 - max effort	7 - very hard 8 - 9 - 10 - very, very hard

Is HIIT Safe?

The 2015 AVERT trial showed that very early mobilization (within 24 hours after stroke) resulted in many adverse events, and significantly worse outcomes at 3 months compared to usual care.[42] There are also risks of arrhythmia, intracerebral hemorrhage, myocardial injury, systolic dysfunction, unstable angina and uncontrolled hypertension that might limit the use of HIIT during the first months (between 1–6 months) in individuals with stroke.[43] Professional supervision is recommended for all high-intensity training and HIIT after stroke, as is careful monitoring of symptoms and vital signs to mitigate risks.[36,38,44]

Recent research shows that HIIT shows no difference in safety outcomes in all other stages (acute >24 hrs, sub-acute, and chronic) after stroke when compared to other interventions. In larger systematic reviews, HIIT was well-tolerated in stroke survivors with no major adverse events and minimal to no adverse effects found in all studies investigated, suggesting that it is a safe and feasible intervention.[45-48]

How Intense Can We Get?

Each patient has different physiological responses to aerobic exercise. What might be easy for a trained individual may be too intense and even life-threatening for someone recovering from a stroke. Traditional methods of measuring maximal exercise capacity such as VO2Max testing or the Buffalo Treadmill test are not feasible for people learning to walk again and are potentially unsafe for individuals at high fall risk or with cardiovascular/neurological conditions.[49]

Submaximal exercise testing offers a safer and more precise approach to gauging aerobic capacity and tailoring exercise intensity by reducing risks and enhancing effectiveness for future interventions.[49] A graded submaximal exercise testing is commonly performed on a recumbent bike or stepper to minimize risk while still measuring resting and peak HR and RPE response during graded aerobic exercise. These findings can help find target HR zones and form objective "stop" criteria for safe and effective training.[50] Exact measures of intensity will vary for each individual patient, but submaximal testing is an effective way to minimize assumption and risk.

Defining "High" Intensity

Currently, the following criteria are used to define high intensity exercise:[41,44,50]

- ≥70% age-predicted HRmax or HRmax during maximal/submaximal testing
- ≥60% heart rate reserve
- Perceived Exertion ≥14 Borg RPE or ≥7 modified Borg RPE

HIIT Improves Walking Recovery after a Stroke

High-intensity Interval Training (HIIT) has proven to be an effective intervention for improving cardiorespiratory fitness and walking in patients after a stroke. Research shows that high-intensity training/interval training significantly improves the maximum rate of oxygen consumption (VO2Max) in stroke patients, a primary marker of aerobic fitness.[48] An initial trial that increased the amount and intensity of stepping during inpatient stroke rehabilitation was found to significantly improve locomotor (steps/day, 10 meter walk speed, 6-minute walk distance) and non-locomotor (transfers & stair climbing) outcomes.[51]

The most recent clinical trials and systematic reviews show that walking/training at a high intensity is significantly more effective for improving ambulatory function (lower extremity functional task performance, gait speed, gait kinematics, and walking capacity/endurance) in all stages after stroke compared to exercise at lower intensities, normal physical therapy, and usual physical activities.[45-48,52-55] Interval training has been widely accepted as the most efficient way to maximize the amount of time spent walking at high intensity.[47]

HIIT Improves Neuroplasticity after a Stroke

General exercise is linked with many well-documented health and mental health benefits.[36] High-intensity aerobic exercise shows similar benefits and has also been shown to positively influence learning, brain function, and neuroplasticity to great extents.[43] Animal and healthy human studies show that learning (both cognitive and motor) is enhanced when primed or followed by vigorous aerobic exercise.[55] It is theorized that high-intensity aerobic exercise enhances neuroplasticity and works through 2 fundamental mechanisms: *1) upregulation of brain-derived neurotrophic factor (BDNF)* and *2) modulation of corticospinal excitability.*

Brain-derived neurotrophic factor (BDNF) plays a major role in use-dependent motor learning and has been studied as a marker of neuroplasticity.[56] Research has found that BDNF facilitates long-term potentiation and dendritic growth & remodeling: both important for experience-based plasticity.[56] In animal studies, inhibition of BDNF resulted in significant motor deficits. Conversely, the injection of BDNF in rats resulted in significant improvements in motor learning, neuroplasticity, and functional recovery.[56] In humans, BDNF is upregulated in the brain by an activity-dependent pathway in response to participation in experiences/activities (such as high-intensity exercise).[57]

Corticospinal excitability is strongly associated with motor learning and is significantly higher during high-intensity aerobic exercise compared to sustained exercise at lower intensities.[55] Intracortical inhibition of excitability is decreased during both motor learning and high-intensity exercise.[55] Modulating corticospinal excitability (*increasing excitability & decreasing inhibition*) through HIIT promotes a practice-related *activation effect* that has been shown to enhance motor learning.[59]

HIIT the Heart, Train the Brain.

Boyne, et al (2019) found that a vigorous aerobic intensity - sufficient to generate lactate accumulation - is needed to increase BDNF during exercise.[55] Further research has found that *just a single bout of HIIT* is sufficient to increase circulating BDNF, corticospinal excitability, and motor skill retention in stroke patients.[60-61] Trials measuring blood-serum levels of BDNF and transcranial magnetic stimulation to evaluate paretic corticospinal excitability show that short bouts of exercise targeting vigorous intensities is more effective for eliciting poststroke neuroplastic change than moderate-intensity continuous exercise.[56-57]

The SAID principle states that the body responds with *specific adaptations to imposed demands*. High-intensity interval training dynamically places unique demands/constraints on multiple specific systems (cardiovascular, respiratory, musculoskeletal, nervous) to result in motor control and motor learning. Training at a high intensity (challenging and *HIITing the heart*) creates a therapeutic environment for enhanced neuroplasticity and learning to *train the brain* to walk after a stroke.[43,57]

FITTing Optimal Parameters into HIIT: An Example Protocol

Boyne, et al (2023) found that a minimum of 12 weeks was the required duration to maximize walking outcomes with HIGT after stroke, with significant improvements every 4 weeks.[63] Their protocol for 45-minute sessions incorporating HIIT is detailed below.[63]

1. *3-minute warm-up of overground walking or NuStep at 30% to 40% of HRR*
2. *10-minute bout of overground HIIT*
3. *20-minute bout of treadmill HIIT*
4. *another 10-minute bout of overground HIIT*
5. *2-minute cool down at 30% to 40% of the HRR.*

<u>HIIT parameters:</u> *repeated 30-second bursts of walking at maximum safe speed, alternated with 30- to 60-second passive recovery periods (standing or seated rest as tolerated), targeting a mean aerobic intensity above 60% of the HRR or intensity of Borg RPE: 14-16.*[63]

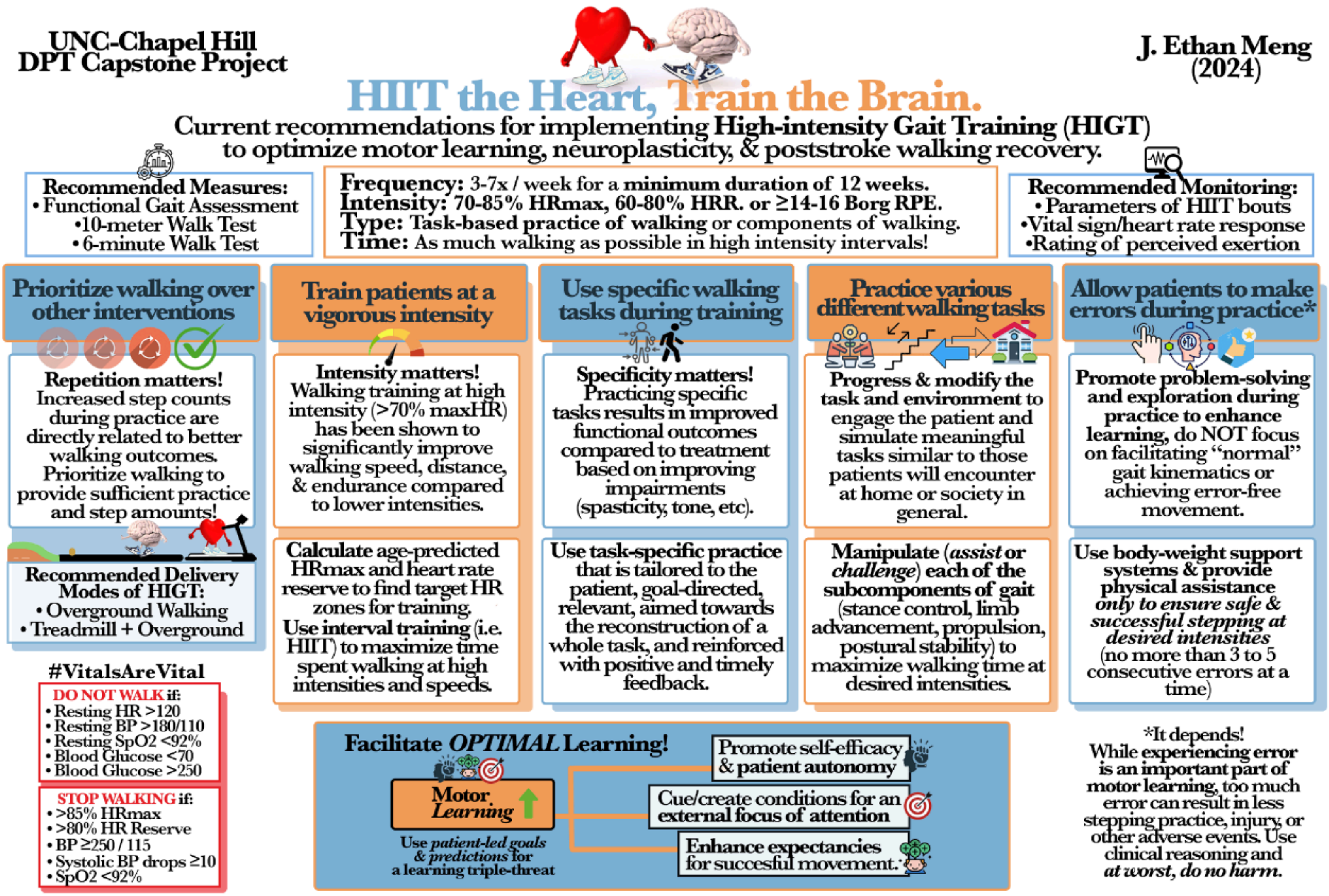
High-intensity Gait Training: Putting it all together

Many active ingredients of experience-based neural plasticity are inherently blended into the intervention of high-intensity gait training (HIGT).[13] HIGT is naturally intense and incorporates large amounts of repetition of a specific task (walking). Learning to walk again is the primary goal of most stroke survivors & is perhaps the most salient activity to practice/take part in.[1,3] Walking is a movement skill that is relevant in almost all life situations and is transferable to other activities and tasks.[13]

There is also ample opportunity to season the active ingredients of HIGT with various spices of motor learning. Clinicians can skillfully create specific walking tasks that apply to normal life, and practice them in various environments to drive & reinforce use-dependent learning and sensorimotor adaptation. Motivational and perceptual learning can be increased by giving patients autonomy, promoting an external focus during tasks, and enhancing expectations for successful movement. HIGT creates a dynamic environment for patients to problem-solve, explore various movements, and learn to walk.

Current recommendations for implementing HIGT

The following graphic summarizes the current recommendations for implementing high-intensity gait training into clinical practice and is printable as a reference poster.[1,13,62-63]



Finally, the following case study outlines a clinical example illustrating the benefits, barriers, and limitations of implementing task-based training and high-intensity gait training into clinical practice.

<u>Case Study</u>

The patient is a 70-year-old F who presented to the ED after being found down by her husband. She was found on the bedroom floor after a presumed fall out of bed, minimally responsive with right-sided weakness and aphasia. Her work-up at the ED revealed acute ischemic stroke 2/2 left M1 occlusion not amenable to reperfusion, and she was admitted to acute care on 1/8/2023. Her hospital course was significant for global aphasia, R hemiparesis, and urinary retention. She had a brief stay in acute inpatient rehab before returning home and starting outpatient therapy (SLP, OT, and PT). Additional case data and detailed progressions can be found in Appendix A.

Subjective History

The patient is a retired nurse with no significant past medical history. Lives with a supportive husband in a single-level home in Wilmington, North Carolina with no steps to enter. Before her stroke, she enjoyed gardening and walking with her 2 dogs.

Examination Data (Outpatient PT Eval: 2/14/2023)

<u>- Body Structure/Function Impairments:</u> right-sided hemiparesis, decreased strength R>L, altered tone (flaccid R UE, low tone in R LE, spasticity in R plantar flexors), and impaired R-side sensation.
<u>- Motor Learning Impairments:</u> apraxia, impaired balance/coordination, impaired sensory processing, communication difficulty (global aphasia: only able to verbalize the word 'come'), impaired ability to comprehend/follow directions and focus on tasks.
<u>- Functional Mobility:</u> Rolling: Mod A; Sit<->Supine: min A, Sit<->Stand: Mod A, Gait: Mod A x2. Functional outcome measures not appropriate this date - FGA: 0/30; 6MWT: 0 ft
<u>- Gait:</u> Pt able to ambulate 15' with rolling walker (RW), R ankle-foot orthosis (AFO), and R hand splint and mod A x2 to advance R LE and facilitate R stance control.
<u>- Gait Impairments:</u> decreased R foot clearance (used AFO), decreased R stance time with decreased L step length, R hyperextension, multiple instances of knee buckling, scissoring, and loss of balance noted during gait.

Intervention Approach

Physical therapy intervention was complex in this case - many body systems were altered and impaired after the patient's stroke. She had many structural impairments such as muscle weakness, spasticity, and altered sensation & tone. She also had many functional impairments as she lacked voluntary control of her right side and required assistance for all functional mobility & transfers. Because of the complexity of her condition, restoring gross muscle strength & normalizing tone through traditional interventions was not sufficient for the patient to learn to walk again. The motor learning process and all interventions had to be tailored and modified specifically to the patient and situation because of her aphasia, motor control deficits, and impaired cognition. *Treatment focused on optimizing motor learning and neuroplasticity for improved walking. The approach used was tailored to the patient's specific needs and goals and largely prioritized the task-specific training of walking, components of walking, and other functional movements.*

Intervention Delivery: "It isn't what you do, but how you do it." - John Wooden

The manner in which therapy was delivered needed to be thoughtful and nuanced because of the patient's communication/cognitive changes after the stroke. She had several impairments (aphasia, apraxia, impaired sensory processing) that made learning complex. Patient-specific factors such as her age and the stage of her stroke (sub-acute) needed to be considered as well as psychosocial factors such as her self-efficacy, perception of physical therapy, hobbies, social support, home environment, and personal goals. The patient required increased processing time to plan and execute movements and had difficulty following/comprehending multi-step directions and complex instructions. Treatment sessions needed to consider these factors and adjust appropriately for effective practice & motor learning. The following table illustrates some interventions used, their rationale, and additional motor learning modifications used to spice up treatment.

Interventions*: ****See Appendix A for more specific parameters of tasks/exercises***

Task	Purpose/Rationale	Examples of Modifications for Motor Learning
Sit to Stand	Salient task (ADL); improve independence/autonomy during transfers; improve stance control and postural stability for gait	- Analogy: "let your nose drip on your toes" to promote anterior weight shift; "imagine a string pulling your head to the ceiling" for tall/upright posture - External focus cue "push the ground away" - "forced use" of paretic LE by putting unaffected LE on block; progressions to a squat/adding weight
Tall Kneel Walking (Forward, retro, lateral walking)	Improve proximal strength (isolates hip), stance control, balance, and limb advancement; floor transfer practice and hip stretching while transitioning in and out of tall kneeling position	- Use low support surface that simulates couch/furniture for assistance; manual assistance/resistance as appropriate - Perform task with a goal (beat a certain time, reach a certain distance/amount of reps before the timer) - Navigate obstacles/various surfaces - Dual task (cognitive-motor; UE object manipulation)
Kicking a Soccer Ball	Improve weight shifting onto paretic LE to unweight contralateral leg for kicking; improve limb advancement and swing phase during gait	- Use of a target (knocking down cones stacked in a tower) to promote external focus of attention - LiteGait to constrain degrees of freedom during initial learning to allow for error while maintaining safety - Involving family members during practice
Stair Climbing	Improve stair performance; train stance control, limb advancement, propulsion, balance	- Manually assist paretic knee/hip to prevent limb collapse and knee hyperextension during stance - Cone added as environmental constraint/external focus/cue to minimize circumduction - "don't knock it over!"; add colored target to step to for external focus - Increase step height; decrease UE support; add recip. arm swing to challenge further
Walking	Most salient/specific activity for patients after stroke; Improves subcomponents of gait, aerobic endurance, LE strength; Elicits neuroplasticity when performed at higher intensities	- Have patient predict how far/fast they will walk. enhance by providing knowledge of results - Manipulate task by "shuttling" various objects, navigating a figure-8 course to practice turning - Alter environment to target various impairments w/ a goal-directed/external focus (hurdles to improve foot clearance, step through ladder to increase step length) - INCREASE INTENSITY; manipulate subcomponents of gait

Motor Learning Considerations:

Verbal instructions were kept simple and concise (one-word/one-step commands as able) to minimize *interference*. Instructions for task practice largely relied on visual *demonstration* to facilitate implicit learning. *Task context* was manipulated to promote a *goal-directed/external focus of attention* as the learner repeated trials of completing a specific task within set parameters. The patient was allowed to make errors during practice to independently problem-solve and explore various movement solutions. The practice environment progressed from closed to open as the patient improved. *Massed practice* of functional tasks was used initially. Task difficulty, complexity, and intensity were carefully progressed and *variable practice* was used as the patient improved to continue to challenge and engage her sufficiently. Extrinsic feedback (knowledge of results) was given in between successful trials with positive feedback throughout to enhance expectancies and provide enhance reinforcement for learning.

As the learner's global aphasia and cognition improved, she was able to verbalize words and communicate more effectively. This provided more opportunities to provide autonomy support, increase verbal feedback/instructions, and improve her self-efficacy. When possible, the patient was empowered to make choices regarding task parameters, session sequencing, and the practice environment. The patient was guided to make *predictions* & set goals to optimize motivation and attention during task practice.

Harnessing a Fall-Free Environment

High-intensity Gait Training (HIGT) was still an emerging intervention at the time of the patient's injury. A major consideration when implementing HIGT is safety - how can a vigorous cardiovascular intensity be achieved without increasing the risk of falls or adverse events? And how can intense walking seem safe and feasible for a patient who is learning to walk after a brain injury? One useful solution to these questions in this specific case was the addition of a LiteGait - a rolling overhead harnessing system.

The clinic acquired a LiteGait overhead support system and was able to use it for gait training with the patient for the first time on 3/29/2023 (visit 17).

The LiteGait allowed the patient to train with more independence and less of the risks involved. The harness system cultivated a fall-free environment for high-intensity overground walking, treadmill training, and other challenging tasks and activities.

A fall-free environment allows the patient to safely experience error, problem-solve, and explore new movements during practice. It also allows for the clinician to focus on increased quality and quantity of practice rather than devoting their attention to guarding and/or manually assisting the patient.

LiteGait Overhead Harness Support System
Photo from *LiteGait:* https://litegait.com/product/lg-400-wd

Implementation of High-intensity Gait Training

Overground walking was selected over treadmill training to enhance carry-over into functional walking around the patient's community and home environments. Overground walking was performed initially in the LiteGait in intervals across the rehabilitation gym. Heavy assistance/bracing was required for successful stepping because of the patient's R lower extremity weakness, impaired motor control, and cognitive/motor planning deficits. The FITT principle illustrates parameters used for HIGT with this patient.

- Frequency: 3x/week
- Intensity: Target HR Zone: 110-134 (age-predicted HRmax of 158); RPE 14-16
- Type: Intervals of high-intensity overground walking in LiteGait
- Time: 45-minute sessions

As training progressed, the patient could walk with more success at higher speeds and with less help. The following table shows snapshots of the use of HIGT to challenge and progress the patient.

Date **Visit #**	**Gait Progression / HIGT Parameters**
2/14/23 (Visit 1)	Gait 15' with RW, R AFO, and R hand splint and mod A x2 to advance R LE and facilitate R stance control.
3/29/23 (Visit 17)	First trial with LiteGait,+2 assist: x400' varying L UE support and PT facilitating increased speed, L wt shift and occasional R foot advancement/placement
4/10/23: (Visit 23)	600' in Lite Gait; PT facilitated faster gait speed in Lite gait with light facil for complete L wt shift. Resting HR: 77, Max HR noted: 120 (76% HRmax)
5/10/23 (Visit 35)	High intensity gait training over level ground with LiteGait, varying L UE support, and varying SBA-CGA; 8 x 100 ft with 1 minute rest breaks
5/23/23 (visit 41)	High intensity interval overground walking with LiteGait, R UE in Omitron, no device or UE support. Bouts of 1 x 600 ft for a total of 21 mins and 0.26 miles walked. Max HR noted: 124 (78% HRmax)
6/06/23 (Visit 45)	High intensity overground walking 4 x bouts of 300 feet with 30-60s rest breaks, no device, R GivMore sling, SBA-CGA throughout for safety (no LiteGait this session) Garmin Watch Stats: Time: 10 mins, Distance: 0.19 miles; Avg. HR: 94bpm, Max HR: 107bpm (68% HRmax). RPE during HIIT: 14.
6/27/23 (Visit 53)	Progressed to treadmill for High Intensity continuous walking at 1.5mph - 2% grade x 8 min, no device or UE assistance

Outcomes

Primary outcomes measures used were the functional gait assessment, 6-minute walk test, and 10-meter walk test. These measures are strongly recommended to measure walking function, endurance, capacity, and speed in patients recovering from a stroke. The patient's functional progress is detailed in the chart below.

Date Visit #	**Ambulation Status**	**Assistance Level**	**Assistive Device(s)**	**10MWT (Speed)**	**6MWT (Distance)**	**FGA (Function)**
02/14 Visit 1	Dependent;	Requires Mod A x 2	RW, R AFO, R hand splint	0 m/s	0 feet	0/30
03/31 Visit 19	Household ambulator	Requires CGA	R PLSO, GiveMor sling, SBQC	0.17 m/s	not tested	not tested
04/20 Visit 28	Household ambulator	Requires CGA	R PLSO, GiveMor sling, SBQC	0.21 m/s	not tested	not tested
05/16 Visit 38	Household ambulator	Requires CGA	R PLSO, GiveMor sling	0.72 m/s	not tested	not tested
06/09 Visit 47	Limited community ambulator;	Requires SBA	None	0.98 m/s	932 feet	20/30
08/02 Visit 60	Full community ambulator	Independent	None	1.03 m/s	1126 feet	23/30

Progress Toward Functional Goals

The patient made significant progress toward identified physical therapy goals, surpassing all of her short-term goals and meeting 4 out of 5 long-term goals. Long-term goals and goal progress upon discharge are listed below:

- LTG 1: In 12 weeks, pt will be mod I with all household sit to stand transfers (MET on 4/20)
- LTG 2: By discharge, Pt will walk 1200' over varied terrain with SPC or no device w/ S maintaining average gait speed of >1.0m/sec to allow greater community access (MET on discharge 08/02)
- LTG 3: By discharge, pt will ascend/ descend 12 steps with rail, reciprocal pattern with S to ensure safety to allow her to visit friends/family (MET on discharge 08/02)
- LTG 4: By discharge, Pt will transfer mod I floor<>stand with 1 UE support to allow participation in gardening. (NOT met (SBA recommended for safety))
- LTG 5: By discharge, Pt will demonstrate ability to carry 5lb grocery bag 1000 ft and navigate multiple turns/changes in direction with no device and SBA to allow for greater independence during ADLs (MET on discharge 08/02)

Discussion

High-intensity gait training is an intervention that is supported by current recommendations for poststroke walking recovery. While there is powerful evidence promoting the use of HIIT in stroke rehabilitation, there are notable limitations that must be addressed. A knowledge gap currently exists regarding the full effects of HIIT on walking outcomes. There is a need for large-scale randomized controlled trials investigating the full effects and safety implications of poststroke HIIT. There is also a need for the development of clinical guidelines and protocols for consistent and optimal implementation in various therapy settings for patients in various stages of recovery after a stroke.

While the patient's overall outcomes were beneficial, it is easy to speculate how they could have been better. Notable limitations in the case example included a lack of resources (equipment & human resources) to provide high-intensity gait training. The LiteGait system was not available until the patient's 17th visit. This was over 2 months s/p initial CVA and hospital admission and only left a few weeks to maximize on the patient's critical time window where the most neuroplastic change occurs. Once the LiteGait was available, use was restricted as many patients benefited from overhead harness support and the LiteGait/walking space was often needed to be shared between multiple patients and providers in the clinic. +2 assistance was also limited because of the high quantity and complexity of the patient census.

Another limitation was the lack of protocol for HIIT bouts and a standardized method of documentation. There was an exorbitant amount of inter-trial variability between sessions of HIIT and greater measures could have been taken to maximize time spent walking at target intensity. One improvement would be to use a specific protocol for HIIT. Having defined parameters for working and recovery periods would make it easier to progress and challenge the patient. Monitoring the exact same parameters each session would also provide helpful insights. The clinic shared one Garmin watch for HR monitoring, and a chest sensor or other medical-grade technology would have been more precise.

Conclusion

Currently, learning is our best hope to optimize walking recovery after a brain injury. Motor control theory has traditionally guided the approach by which clinicians facilitate motor learning. Current theory suggests that dynamic systems self-organize according to individual, task, and environmental constraints to produce skilled movement and learning. Motor learning should involve goal-directed task-specific practice of functional movements and should be optimized to enhance the learner's motivation and attention. Neuroplasticity subserves learning and is influenced by various active ingredients that should be included during training/practice experiences. High-intensity interval training (HIIT) is an emerging intervention that has been found to significantly improve walking outcomes in patients in all stages poststroke. Even a single bout of HIIT to the heart has been shown to elicit significant changes in brain-derived neurotrophic factor and corticospinal excitability to train the brain to walk again. High-intensity gait training should be implemented and prioritized during neurorehabilitation in order to enhance motor learning, drive neuroplasticity, and improve walking outcomes in patients recovering from a stroke.

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<u>Supplementary Material (Case Data; Posters for Clinical Reference)</u>

Appendix A:
CASE DATA - chronological summary of progressions, interventions, goals/goal status:

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Hi Ethan- here are some of the treatment interventions I started and you continued- Hope you are doing well!

<u>02/14/2023: Visit 1: Outpatient PT Eval:</u>
POC 3x/wk:
<u>Gait:</u> 15' with RW and R hand splint mod A x2 to advance R LE, facilitate R stance control
<u>Short Term Goals</u>

STG 1: In 4 weeks pt will be mod I with bed mobility
STG 2: In 4 weeks, pt will walk 200' over level ground with min A
STG 3: In 4 weeks, Pt will ascend/descend 4 steps with min A
STG 4: in 4 weeks, pt will be able to transition floor<>chair with mod A to allow for safe fall recovery

<u>Long Term Goals</u>

LTG 1: In 12 weeks, pt will be mod I with all household sit to stand transfers
LTG 2: In 12 weeks, Pt will walk 1000' over varied terrain with SPC and SBA maintaining average gait speed of 0.65m/sec to allow greater community access
LTG 3: In 12 weeks, pt will ascend/ descend 12 steps with rail, reciprocal pattern with S to ensure safety to allow her to visit friends/family

<u>2/15/2023: visit 2:</u>
<u>Assessment:</u> Pt tolerated session well. She was able to increase gait distance to 60' with min-modA for R foot placement and stance stability. Able to use PLSO. Today, did note hyperextension in mid-terminal stance but easily facilitated with manual cues/assist from PT for knee stability. Following forced weight bearing activities at stairs, pt had significant improvement in reciprocal gait pattern and R LE activation. She continues to benefit from skilled PT to increase safety and independence with functional mobility.
Exercise 1: w/c > mat toward L with minA; nustep > w/c toward R with modA stand pivot
Exercise 2: sit <> stand from mat x6 reps with PT providing downward force to R knee for forced weightbearing/joint approximation
Exercise 3: donned R PLSO in sitting
Exercise 4: gait 2x60' and 1x40' with min-modA with SBQC, PLSO and w/c follow. Pt able to advance R LE without assist, PT facilitating knee stability to prevent excessive flexion/hyperextension in mid stance
Exercise 5: at 6" stairs with L UE support: R stance with L foot fwd on 6" step for 10-15 sec hold with PT providing downward force to R hip and knee for stance stability

Exercise 6: fwd step ups with R lead at 6" step with L UE support and facilitation to R LE as above 2x6 reps
Exercise 7: Nustep wtih LEs only L1 x2 minutes with active assist for R LE extension

<u>2/24/2023: visit 6:</u>
Assessment: Pt was able to I'ly advance R LE in swing 70-90% of steps when walking with QC. (slip sock also donned). Pt and spouse motivated to begin walking at home, therefore today we looked at ordering off shelf R small PLSO and R wide tipped cane. They will order this weekend and bring to PT when delivered. PT notes R shoulder sublux- with gait progression, PT will discuss need for shoulder support (possible givemor)
Exercise 1: w/c<>mat CGA; supine<>sit mod I
Exercise 2: PNF facilitation in supine and L sidelying for R LE flex/ext patterns to improve swing phase of gait
Exercise 3: gait overground with SBQC, R PLSO, R slip sock, R givemor sling,2 x90' with varying CG-minA for postural control and R LE complete swing; 40'x1 trial with wide tipped cane with min A for balance and R LE advance in swing

<u>3/6/2023: visit 10:</u>
Independence Level: moderate assist (50% patient effort)
Assistive Device(s) Utilized: AFO, sling and small base quad cane (R PLSO (off shelf from amazon); R slip sock; R givemor)
Gait Distance: household
Gait Distance: 90 feet
Gait Pattern: foot drag - R, foot drop - R, decreased stance time - R and flexed knee - R

<u>3/10/2023: visit 13:</u>
Assessment: Following PNF for R LE motor control pt was able to I'ly advance R LE in swing 70-90% of steps when walking with QC. (slip sock also donned). Pt and spouse motivated to begin walking at home, therefore today we looked at ordering off shelf R small PLSO and R wide tipped cane. They will order this weekend and bring to PT when delivered. PT notes R shoulder sublux- with gait progression, PT will discuss need for shoulder support (possible givemor)
Exercise 1: w/c<>mat CGA; supine<>sit mod I
Exercise 2: PNF facilitation in supine and L sidelying for R LE flex/ext patterns to improve swing phase of gait
Exercise 3: gait overground with SBQC, R PLSO, R slip sock, R givemor sling,2 x90' with varying CG-minA for postural control and R LE complete swing; 40'x1 trial with wide tipped cane with min A for balance and R LE advance in swing

<u>3/29/2023: visit 17:</u> LITE GAIT / HIGT initiated on 3/29/2023 (this is when we got the Lite gait for our clinic)
Exercise 1: gait with Lite gait,+2 assist x400' varying L UE support and PT facilitating speed, L wt shift and occasional R foot advancement/placement

Exercise 2: stairs 4x2 with L UE support and CG-min A ,L lead and reciprocal to ascend;R and L lead to descend step to pattern

<u>3/31/2023: visit 19:</u>
Gait Trial:
Independence Level: contact guard assist
Assistive Device(s) Utilized: AFO, sling and small base quad cane (R PLSO (off shelf from amazon); R givemor)
Gait Distance: household
Gait Distance: 200 feet
Gait Pattern: foot drag - R, foot drop - R, decreased stance time - R and flexed knee - R
Surfaces: level
Gait Speed: 0.17 meters/sec
Gait Trial 1 Comments: In PT gait training with Lite gait for increased intensity able to walk 600' bouts with brief standing breaks; able to achieve gait speed of 0.50m/sec in Lite gait with tactile facilitation for complete L wt shift to allow full R step length.

<u>4/3/2023: visit: 20</u>
Assessment: Pt was able to self cue to shift L in stance to clear R LE in swing on first Lite gait walk; PT facilitated faster gait speed in Lite gait with light facil for complete L wt shift; progressed reciprocal pattern on stairs- most difficulty with L lead descend due to R knee instability
Exercise 1: warm up Nustep L1x3min with B LE and L UE; x2 min LE only with tactile cues for R LE alignment (tends to IR)
Exercise 2: gait with QC, R PLSO and CGA 50'x2 then 50'x1 no device with min A for postural control, L wt shift
Exercise 3: gait with Lite gait,+2 assist x400' varying L UE support and PT facilitating speed, L wt shift and occasional R foot advancement/placement.

- RHR 70; max achieved walking in Lite gait 86

Exercise 4: stairs 4x2 with L rail, reciprocal w CGA to ascend, min A for R LE placement on descend

<u>4/10/2023: visit 23:</u> High Intensity Training: Resting HR 77, max 120 w/ HIGT 600' in Lite Gait

<u>4/20/2023 Visit 28:</u> emerging R ankle DF
Independence Level: contact guard assist
Assistive Device(s) Utilized: AFO, sling and small base quad cane (R PLSO (off shelf from amazon); R givemor)
Gait Distance: household
Gait Distance: 300 feet
Gait Pattern: foot drag - R, foot drop - R and trendelenburg - Uncompensated
Surfaces: level

Gait Speed: 0.21 (improved from 0.17) meters/sec
Gait Trial 1 Comments: In PT gait training with Lite gait for increased intensity able to walk 800' bouts with brief standing breaks; able to achieve gait speed of 0.88m/sec in Lite gait with tactile facilitation for complete L wt shift to allow full R step length
With cane and PLSO pt can walk up to 80' with close guarding from PT with high concentration
In Pt gait training without cane and some without PLSO with CG-minA for wt shift/ balance.

5/5/2023: visit 34
Session conducted today without use of cane and without R PLSO; Pt has varying stability with standing and gait activities; impaired sensory processing through R LE combined with impulsivity impacting safety therefore PT recommends constant CG with all standing/ walking activities. With direct multi-modal cues pt can walk and navigate small obstacles and curbs with CGA; with distraction she can have significant LOB with poor ability to recover BOS or midline posture; frequently throughout session she required mod-maxA for balance recovery. Will continue to progress gait safety and optimize R hemibody motor control as able.
Exercise 1: Nustep L1x5min LE only to facil R LE motor control; tactile cues and VC's for activation/pacing
Exercise 2: gait over level ground without device and varying CG-modA x200'; trial of R 2lb ankle wt x100' with no improvement noted.
Exercise 3: fwd and lateral stepping over three QC on floor with focus on R LE foot clearance, varying CG-maxA for balance and cues for sequencing, x4 laps
Exercise 4: sit<>stand with tactile cue for R LE activation; trial of R bias with L LE on step
Exercise 5: standing balance with R hip taps, CGA
Exercise 6: gait with quad tipped cane outdoors down ramp, curb step to car with CG-min A

5/10/2023 visit 35:
Exercise 1: High intensity gait training over level ground with LiteGait and varying SBA-min A to steady/facilitate R weight acceptance in stance phase; 6 x 100 ft
Exercise 2: gait over level ground without device and varying CG-modA 1 x 75 ft from mat to ballet bar; 1 x 50 feet from ballet bar to stairs
Exercise 3: lateral stepping 5 x 10 steps each direction, SBA with L UE assist for 3 sets, CGA with no UE assist and facilitation at pelvis for 2 sets.
Exercise 4: Sit <> stand x 10 reps, cueing for R LE activation, manual facilitation to reduce R knee hyperextension
Exercise 5: standing balance with R hip taps x 5, CGA
Exercise 6: R LE stair/ground taps 2 x 10 with L LE on first step and L UE use of railing, facilitation to increase R hip flexion and to clear step
Exercise 7: Lateral step up (R LE leading), 1 x 10 with UE support and CGA-mod A, 1 x 10 SBA

<u>5/12/2023: visit 37:</u>
Exercise 1: High intensity gait training over level ground with LiteGait, varying L UE support, and varying SBA-CGA; 8 x 100 ft
Exercise 3: R lateral weight shifts with LiteGait and verbal/tactile cueing to knock over therapist with hips x 30 reps
Exercise 4: L LE step ups with LiteGait, cueing for R lateral weight shift, 2 x 10 onto mat at lowest height, CGA-min A transitioning to CGA to facilitate weight shift and stabilize pelvis
Exercise 5: Ball kicks B LEs x 7 minutes in LiteGait, cueing to maintain balance, prepare immediately for next kick, and weight shift appropriately onto R LE.
Exercise 6: Sit <> stand 1 x 10 cueing for incr. R LE activation
Exercise 7: 10 mins gait training with no device and CGA, navigating obstacles and turns around clinic.
Exercise 8: 7 mins shuttle drill around treatment table carrying and transferring 4 cones one at a time stacked on chairs at opposite ends of table with CGA and no device
Exercise 9: Stacking and unstacking cones in a mini squat, 2 sets x 4 cones, no device, CGA-min A to steady

<u>05/16/2023: visit 38 : BERG 38/56 Independence Level: contact guard assist</u>
Assistive Device(s) Utilized: AFO and sling (R PLSO (off shelf from amazon); R givemor)
Gait Distance: household
Gait Distance: 200 feet
Gait Pattern: foot drag - R, foot drop - R and trendelenburg - Uncompensated
Surfaces: level
Gait Speed: 0.72 (improved from 0.21 with SBQC) meters/sec
Gait Trial 1 Comments: Ambulation post high intensity gait training in Litegait with no device, R UE sling, and AFO.

<u>Assessment:</u> Pt ambulated 200' feet with light CGA, steady gait, 1 mild self-corrected LOB. Displays mildly reduced R LE stance control with mild trendelenburg noted in R stance. Displays notable improvements in R foot clearance during swing phase. Responds well to cueing for L side recip. arm swing but has tendency to brace it against body.

5/23: <u>visit 41:</u>
Exercise 1: High intensity level ground gait training with LiteGait, R UE support with Omitron, no device or UE support, x 600 ft continuous HR max 124 Lite gait training 21 min for 0.26mile
Exercise 2: Gait 2 x 100 ft with hurdles in LiteGait holding cup
Exercise 3: Side stepping x 5 minutes, side stepping with hurdles x 5 minutes
Exercise 4: SL hedgehog taps focusing on R LE stance control x 5 minutes, hedgehog taps positioned on LiteGait Rails x 5 minutes
Exercise 5: Sit <> stand: 1 x 10, mini squat: 1 x 10

6/6/2023: visit 45:
Assessment: Pt demonstrates improved ability to navigate and sequence turns and changes in direction, only requiring SBA-CGA during high intensity overground walking. Demonstrated good response to session without LiteGait support, demonstrating appropriate vital sign responses and RPE within target training range during HIIT. Still requires increased demonstration and facilitation for novel skills/movements, with increased balance reactions/safety awareness noted but still requiring SBA-intermittent CGA during functional mobility. Demonstrates decreased rollover/pushoff in R LE during terminal stance, plan to address during gait training next session as able.

Exercise 1: High intensity overground walking 4 x bouts of 300 feet with 30-60s rest breaks in between, no device, GivMore sling, SBA-CGA

- Garmin Watch Stats: Time: 10 mins, Distance: 0.19 miles; Avg. HR: 94bpm, Max HR: 107bpm, Max Cadence: 128 SPM.
- RPE during HIIT: 14.

Exercise 2: Forward/lateral step up leading with R LE 2 x 10 each, intermittent use of handrail for forward, requires CGA when not holding rail
Exercise 3: Hedgehog taps x 5 minutes stepping over square with each LE, turning in square to tap hedgehog with both LEs x 5 minutes CGA
Exercise 4: Side stepping through ladder (step to) x 3 sets each direction SBA-CGA.
Exercise 5: Forward walking through ladder with reciprocal gait pattern, backward walking through ladder step to, x 3 sets each direction SBA-CGA
Exercise 6: Retro walking 2 x 50 ft, therapist CGA
Exercise 7: "Shuttle Drill" x 30 ft x 3 sets each direction

6/09/2023: visit 47 : FGA 20/30
Gait Trial 1:
Independence Level: stand-by
Gait Distance: limited community
Gait Distance: 932 (on 6MWT) feet
Symptoms Noted During/After Treatment: fatigue
Gait Speed: 0.98 meters/sec
Gait Trial 1 Comments: Decreased R heel strike/push off noted, slight toe out on R LE with tendency to scuff R foot
INTENSITY: Avg HR: 93bpm, Max HR: 104bpm, 1 seated rest break. Steps: 295 over 475' distance.

<u>Long Term Goals</u>

LTG 1: In 12 weeks, pt will be mod I with all household sit to stand transfers (MET)
LTG 2: By discharge, Pt will walk 1200' over varied terrain with SPC or no device w/ S maintaining average gait speed of >1.0m/sec to allow greater community access (PROGRESSING; current gait speed 0.72 m/s)

LTG 3: In 12 weeks, pt will ascend/ descend 12 steps with rail, reciprocal pattern with S to ensure safety to allow her to visit friends/family (MET)

- Updated Goal 6/9/23: by discharge, Pt will demonstrate ability to ascend/descend 1 flight of stairs mod I holding 5 pound grocery bag for improved ADL performance/independence with functional mobility

LTG 4: By 6/30/2023 Pt will transfer floor to stand with LUE support and CGA to allow her to participate in HEP on the floor (MET)

- Updated Goal 6/9/23: by discharge. Pt will demonstrate ability to carry 5lb grocery bag 1000 ft and navigate multiple turns/changes in direction with no device and SBA to allow for greater independence during ADLs

Gait Trial 2:
Independence Level: stand-by assist
Gait Distance: 100 feet
Gait Trial 2 Comments: Pt able to ambulate over uneven surfaces with minimal R foot drag, SBA, no device.

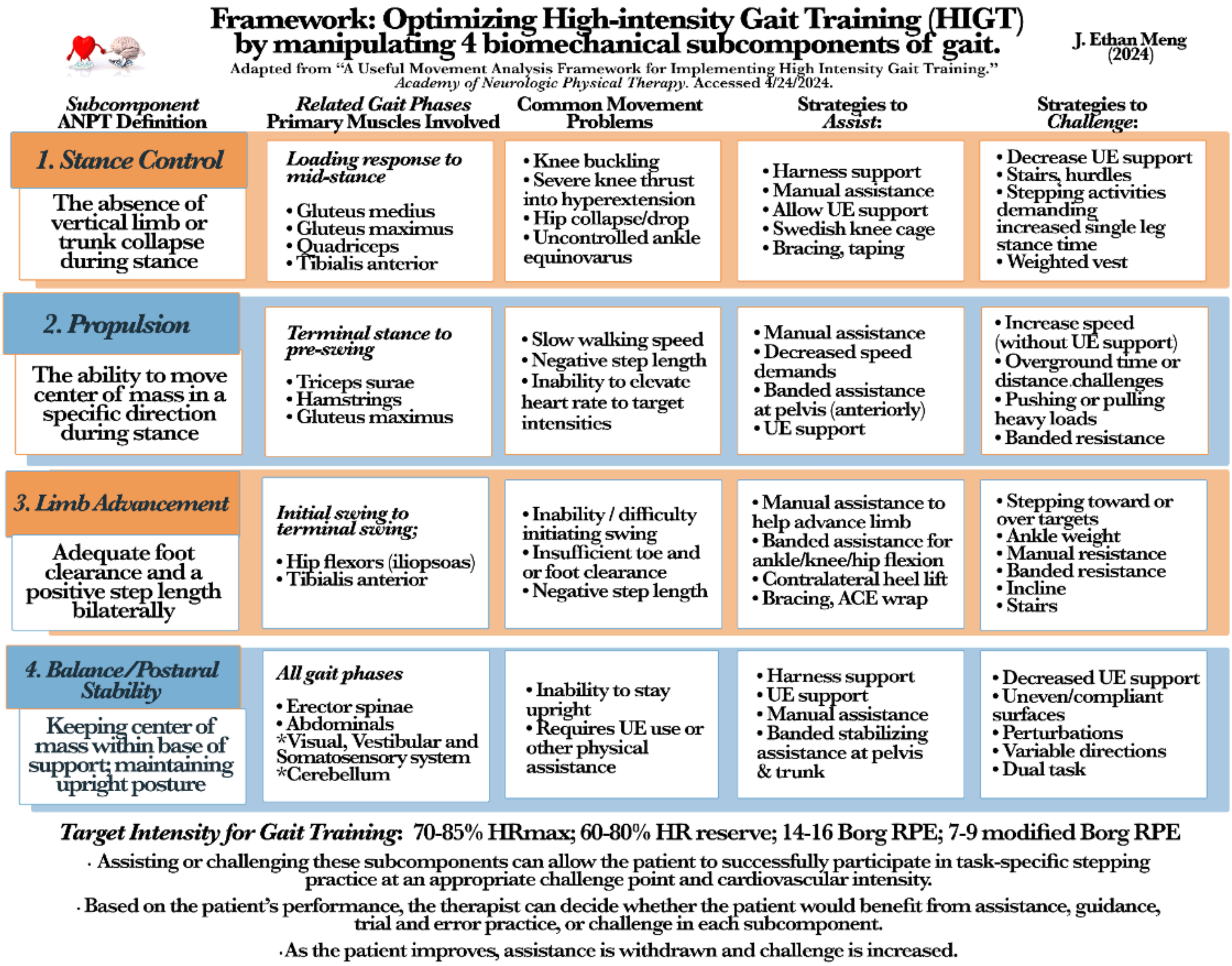
6/27/2023: progressed off Lite Gait to treadmill for High Intensity at 1.5mph 2% grade x8min

07/20/2023: 6MWT 1073'
Gait Trial 1:
Independence Level: modified independent (safety concern) - no devices
Gait Distance: limited community
Gait Pattern: foot drag - R and spastic (intermittent/ rare)
Gait Speed: 0.87 meters/sec
Gait Trial 1 Comments: Decreased R heel strike/push off noted, slight toe out on R LE with tendency to scuff R foot

DISCHARGE 8/2/2023 visit 60: 6MWT 1126 no device; FGA 23/30
Gait Trial 1:
Independence Level: independent
Assistive Device(s) Utilized: none
Gait Distance: full community
Gait Pattern: decreased stance time - R
Gait Speed: 1.03 meters/sec
Gait Trial 1 Comments: Able to safely walk and navigate terrain while carrying 5lb grocery bag over L shoulder.

Appendix B: Graphics for Clinical Reference

Figure A: Framework: Optimizing High-intensity Gait Training by manipulating 4 biomechanical subcomponents of gait



Framework: Optimizing High-intensity Gait Training (HIGT) by manipulating 4 biomechanical subcomponents of gait.

J. Ethan Meng (2024)

Adapted from "A Useful Movement Analysis Framework for Implementing High Intensity Gait Training." *Academy of Neurologic Physical Therapy*. Accessed 4/24/2024.

Subcomponent ANPT Definition	*Related Gait Phases* Primary Muscles Involved	Common Movement Problems	Strategies to *Assist*:	Strategies to *Challenge*:
1. Stance Control The absence of vertical limb or trunk collapse during stance	***Loading response to mid-stance*** • Gluteus medius • Gluteus maximus • Quadriceps • Tibialis anterior	• Knee buckling • Severe knee thrust into hyperextension • Hip collapse/drop • Uncontrolled ankle equinovarus	• Harness support • Manual assistance • Allow UE support • Swedish knee cage • Bracing, taping	• Decrease UE support • Stairs, hurdles • Stepping activities demanding increased single leg stance time • Weighted vest
2. Propulsion The ability to move center of mass in a specific direction during stance	***Terminal stance to pre-swing*** • Triceps surae • Hamstrings • Gluteus maximus	• Slow walking speed • Negative step length • Inability to elevate heart rate to target intensities	• Manual assistance • Decreased speed demands • Banded assistance at pelvis (anteriorly) • UE support	• Increase speed (without UE support) • Overground time or distance challenges • Pushing or pulling heavy loads • Banded resistance
3. Limb Advancement Adequate foot clearance and a positive step length bilaterally	***Initial swing to terminal swing;*** • Hip flexors (iliopsoas) • Tibialis anterior	• Inability / difficulty initiating swing • Insufficient toe and or foot clearance • Negative step length	• Manual assistance to help advance limb • Banded assistance for ankle/knee/hip flexion • Contralateral heel lift • Bracing, ACE wrap	• Stepping toward or over targets • Ankle weight • Manual resistance • Banded resistance • Incline • Stairs
4. Balance/Postural Stability Keeping center of mass within base of support; maintaining upright posture	***All gait phases*** • Erector spinae • Abdominals *Visual, Vestibular and Somatosensory system *Cerebellum	• Inability to stay upright • Requires UE use or other physical assistance	• Harness support • UE support • Manual assistance • Banded stabilizing assistance at pelvis & trunk	• Decreased UE support • Uneven/compliant surfaces • Perturbations • Variable directions • Dual task

Target Intensity for Gait Training: **70-85% HRmax; 60-80% HR reserve; 14-16 Borg RPE; 7-9 modified Borg RPE**

· Assisting or challenging these subcomponents can allow the patient to successfully participate in task-specific stepping practice at an appropriate challenge point and cardiovascular intensity.

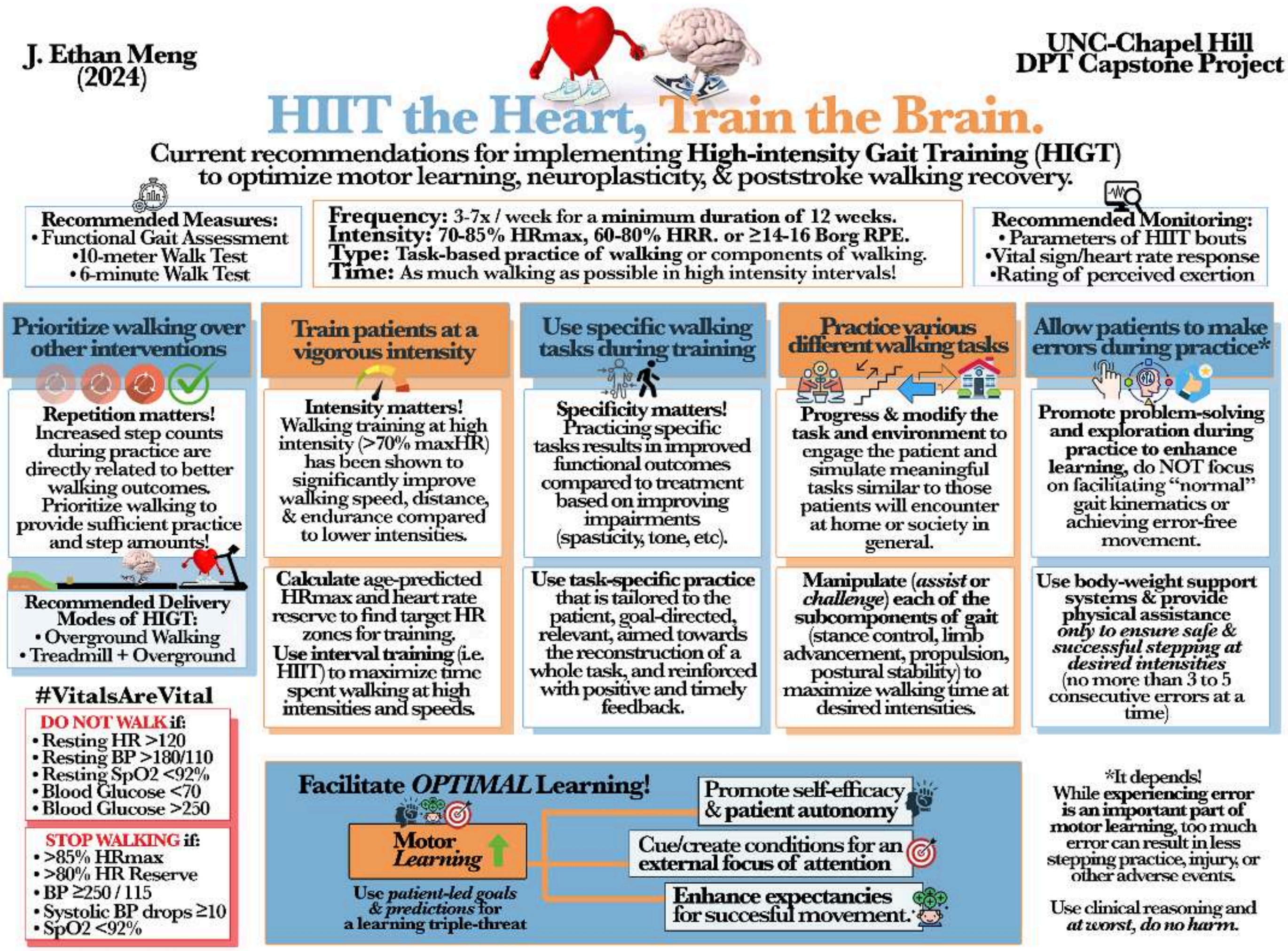
· Based on the patient's performance, the therapist can decide whether the patient would benefit from assistance, guidance, trial and error practice, or challenge in each subcomponent.

· As the patient improves, assistance is withdrawn and challenge is increased.

The above framework was was printed as a 20x14 poster for clinical reference and was adapted from the following references.

- "A Useful Movement Analysis Framework for Implementing High Intensity Gait Training". *Academy of Neurologic Physical Therapy.* Accessed 4/24/2024. https://www.neuropt.org/docs/default-source/cpgs/locomotor/biomechanical-subcomponents-explained---rg-2022.pdf?sfvrsn=8f535d43_0
- Moore JL, Bø E, Erichsen A, et al. Development and Results of an Implementation Plan for High-Intensity Gait Training. *J Neurol Phys Ther*. 2021;45(4):282-291. doi:10.1097/NPT.0000000000000364

Figure B: Current recommendations for implementing High-intensity gait training to optimize motor learning, neuroplasticity, & poststroke walking recovery.



The graphic above was printed as a 20x14 poster for clinical reference and was constructed using recommendations from various references in this project.

The End. :)