

Motor Learning During Poststroke Gait Rehabilitation: A Case Study

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Introduction: To develop more effective gait rehabilitation strategies, it is important to understand the time course of motor learning that underlies improvements achieved with gait training. The purpose of this case study was to evaluate motor learning through the measurement of within-session and across-session changes in gait biomechanics during the first and sixth weeks of a 6-week clinical gait training program.

Case Description: A 47-year-old man with poststroke left hemiparesis participated in the study (15.5 months poststroke, lower extremity Fugl-Meyer score of 12).

Intervention: The subject participated in 6 weeks of training with 3 sessions per week, comprising fast treadmill walking and functional electrical stimulation to plantar and dorsiflexors. In one training session during the first and sixth weeks, paretic propulsion and swing phase knee flexion were measured during a pretest (before the training session), posttest (after the training session), and retention test (48 hours after training).

Outcomes: After 6 week of training, the subject's gait speed increased from 0.38 to 0.57 m/s; there was a 55.4% improvement in paretic propulsion and 25% increase in swing phase knee flexion. Examination of change scores revealed greater within-session gains and greater retention during the first versus sixth weeks of gait training for both paretic propulsion and knee flexion.

Discussion: We demonstrate the feasibility and advantage of using within- and across-session changes for evaluating motor learning during clinical gait rehabilitation. An understanding of the time course of motor learning that underlies gait training can guide the development

of novel strategies and dosing regimens to increase the efficacy of each session of gait rehabilitation.

Video Abstract available (See Video, Supplemental Digital Content 1, <http://links.lww.com/JNPT/A72>, for more insights from the authors.)

Key words: *gait biomechanics, gait training, functional electrical stimulation, hemiparesis, motor learning, treadmill, stroke*

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BACKGROUND AND PURPOSE

Even after discharge from rehabilitation, gait deficits are prevalent in stroke survivors.^{1–3} Common gait impairments after stroke include reduced flexion at the hip, knee, and ankle during the swing phase. Decreased push-off force generation by the paretic limb during terminal stance is another critical gait impairment shown to be related to reduced swing knee flexion, hemiparetic severity, and walking speed.^{4–7} Although there is consensus in the rehabilitation literature that gait retraining can improve poststroke walking performance, agreement is lacking about which rehabilitation intervention or dosing regimen is most efficacious.^{8–11} One factor contributing to the inconclusive nature of current evidence is that there are several gaps in our understanding of mechanisms and time course of changes underlying stroke gait rehabilitation. Typically, rehabilitation studies demonstrate improvements in global measures of walking (eg, gait speed or endurance) after 6 or 12 weeks of gait training.^{8–17} Although such intervention studies are important to validate the *efficacy* of rehabilitation, they provide little information about the *within- and across-session time courses* underlying improvements in gait achieved with gait rehabilitation.^{8,10,11,14,18,19}

Motor learning is a set of processes associated with practice, training, or experience that produce relatively permanent changes in behavior.²⁰ Motor learning studies use diverse paradigms (eg, movement against resistive force fields, weighted walking tasks, and robotic assistance) and make measurements of within-session changes in performance and persistence of the learned motor skills minutes or hours after training (retention).^{21–23} An individual's ability to learn motor skills is a crucial component of gait rehabilitation.^{21,23,24} Motor learning concepts typically applied during clinical rehabilitation, however, are often derived from animal studies or in human experiments done within controlled laboratory environments involving nonfunctional movements, and in able-bodied

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individuals.^{23,25–31} Given the role of motor learning in rehabilitation, it is critical to understand if, when, and to what extent motor learning occurs during gait training.

“FastFES,” the combination of fast treadmill training with functional electrical stimulation (FES) of ankle plantar and dorsiflexor muscles, is a novel and promising poststroke gait rehabilitation intervention.^{32–38} The FastFES intervention capitalizes on principles derived from gait biomechanics, muscle physiology, and motor learning to target-specific poststroke gait deficits such as slowed walking speed, decreased paretic propulsion, decreased knee, and ankle flexion during swing. The FastFES intervention includes high-intensity treadmill walking practice, overground walking practice, and alternating practice with and without FES. Twelve weeks of FastFES gait training produces improvements in gait impairments, walking function, activity, and participation poststroke.^{37,39}

Although motor learning is a central mechanism underlying rehabilitation after stroke,^{31,40} fundamental questions about the role of motor learning during clinical gait rehabilitation remain unanswered. For example, does poststroke gait performance improve within one gait training session? If improvements in gait are achieved within one training session, do these improvements persist by the beginning of the next training session? In addition to the gaps in literature about motor learning processes underlying clinical poststroke gait training, there is dearth of information regarding the time course of motor learning during gait rehabilitation. In a recent study evaluating gait biomechanics, gait function, and participation in individuals poststroke every 4 weeks during 12 weeks of FastFES training, we showed that the time courses of improvements in gait biomechanics (eg, paretic propulsion and swing phase knee flexion) versus gait function (eg, gait speed, endurance, and dynamic balance) were different.³⁹ Improvements in gait biomechanics seemed to reach a plateau by the fourth training week, whereas improvements in gait function continued throughout 12 weeks of training.³⁹ Thus, the time course of changes in poststroke gait may differ across different types of outcome variables (eg, structure and function vs activity) and may also differ during early versus late phases of gait training. The purpose of this case study was to evaluate motor learning (assessed via within-session changes in gait performance and across-session retention of improved gait biomechanics 48 hours after a training session) during the first and sixth weeks of a 6-week FastFES gait training program. We hypothesized that if the FastFES training session induces learning of gait biomechanics that are the target of training, we would observe within-session improvements in gait performance (online gains) and retention of improved gait patterns at the start of the next training session (48 hours later). We also hypothesized that the magnitude of motor learning would differ early (first week) versus late (sixth week) during training.

CASE DESCRIPTION

A 47-year-old man with poststroke left hemiparesis participated in the study. The study participant was 15.5 months poststroke, and scored 12 on the lower extremity Fugl-Meyer scale (measure of lower extremity motor function; maximum score 34). His magnetic resonance imaging scan indicated a right middle cerebral artery infarct with restricted diffusion

involving the right lenticular nucleus, frontal lobe, internal capsule, and temporal lobe. His Berg balance score was 39 (measure of balance; maximum score 56), timed up and go test score was 30.3 seconds (measure of functional mobility; score for community dwelling able-bodied adults >13.5 seconds),⁴¹ and functional gait assessment score was 9 (measure of walking performance; maximum score 30). The subject ambulated without an ankle foot orthosis but with the assistance of a single-point cane. At baseline, his self-selected overground gait speed was 0.38 m/s, and distance ambulated during the 6-minute walk test was 146.6 m. The subject scored 29 on the Mini-Mental State Examination and 7 on the Geriatric Depression Scale. The subject did not have neurological disease other than stroke, cerebellar signs, neglect, hemianopia, insulin-dependent diabetes, orthopedic problems affecting walking, or inability to communicate with investigators. All study procedures were approved by the institutional human subjects review board.

INTERVENTION

As part of this case study, the subject participated in 6 weeks (18 sessions) of gait training. To evaluate motor learning, changes in gait biomechanics within and across training sessions were evaluated by conducting gait analysis during 4 of the training sessions (Figure 1). Gait analysis was conducted during sessions 1 and 2 of the first training week and during sessions 16 and 17 of the sixth training week. In addition, the subject's gait speed and gait biomechanics were evaluated during tests conducted at baseline (before start of the first training session) and at the start of the sixth week to assess overall changes in his walking function and biomechanics after training.

Methods for FastFES Gait Training

Gait training included a combination of fast treadmill walking and functional electrical stimulation to the plantar and dorsiflexor muscles of the paretic ankle (FastFES). The fast (training) speed was determined as the fastest speed at which the subject could walk for 4 minutes. The subject's fast or training speed was 0.42 m/s during the first training week, and had progressed to 0.60 m/s during the sixth training week. Each FastFES training session comprised a total of 36 minutes (six 6-minute bouts) of walking practice. Seated rest breaks were provided between bouts. Bouts 1 to 5 comprised treadmill walking at the fast speed, with alternating 1-minute periods of fast walking with and without FES. During periods of walking with FES, FES was delivered to ankle dorsiflexor muscles during the paretic swing phase and to ankle plantarflexor muscles during the paretic terminal stance phase.^{32–34,36} Functional electrical stimulation was delivered via surface electrical stimulation electrodes attached to skin overlying the ankle dorsiflexor (2" × 2", TENS Products, CO) and plantarflexor muscles (3" × 5", VersaStim, NY). FES intensity was set at the start of the training session, as described in previous publications.^{32–34} Intermittent application of FES was provided to encourage the subjects to practice the timing of muscle activation provided by FES during intervening periods without FES. Bout 6, the last training bout, comprised 6 minutes of overground walking without FES. During bout 6, the subject walked at a fast pace and was instructed to mimic

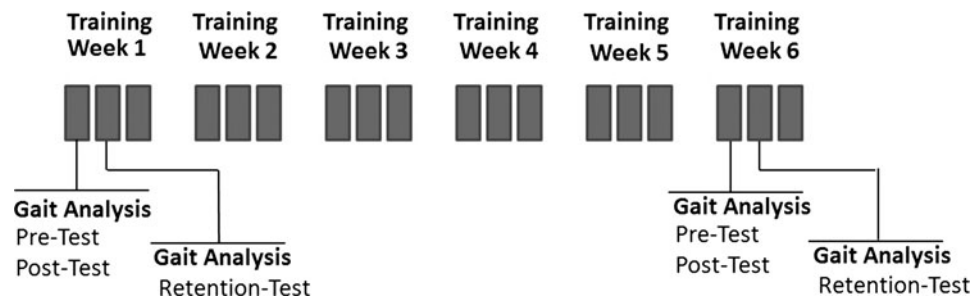


Figure 1. A schematic showing the experimental protocol for the case study. Each bar represents a FastFES training session. Pretest, posttest, and retention test data collected during week 1 and week 6 of training were used to compute change scores for assessing motor learning.

the walking patterns he practiced on the treadmill during the 5 preceding treadmill training bouts.

Methods for Gait Analysis

The biomechanical impairments targeted by the intervention (paretic propulsion and swing phase knee flexion) were used as outcome measures of gait performance. During the first training session, 3-dimensional gait analysis was performed during a pretest (before the training session) and posttest (after the training session), and a retention test was conducted at the start of the next training session (48 hours after the first training session). Similarly, after the subject had completed 5 weeks of training, during the first session of training week 6, gait analysis was performed during a pretest and posttest, and a retention test was conducted at the start of the next session (Figure 1). Gait speed and biomechanical data obtained during the pretest of week 1 and pretest of week 6 were used to determine the overall improvement in gait with training (ie, therapeutic effect).

During these pre-, post-, and retention tests, an 8-camera motion analysis system (Motion Analysis, Santa Rosa, CA) was used to measure positions of reflective markers attached to the subject during walking at the self-selected gait speed. For consistency and to prevent the influence of changes in speed on gait biomechanics, the same self-selected speed (determined before training) was used for all the gait analysis sessions during the first and sixth weeks. Reflective markers were attached to bilateral thigh, shank, foot segments, and pelvis.⁴² During gait analysis, the subject walked on a split-belt treadmill instrumented with force platforms embedded within each belt (Bertec Corp, Columbus, OH). Marker and ground reaction force data were sampled at 1000 and 100 Hz, respectively. During the pre-, post-, and retention tests, the subject walked without FES and without an orthosis. The subject wore an overhead support harness with no body weight support for safety.

Gait events (initial contact and foot-off) were determined using the vertical ground reaction forces (GRFs). The GRF data were normalized to the subject's weight. For the antero-posterior ground reaction force data from each stride, the phase between the point where the anteroposterior ground reaction force crossed zero (transition from posterior to anterior) and the end of the stance phase was identified as the portion of the gait cycle when the subject demonstrated anteriorly di-

rected ground reaction forces, or push-off forces. The paretic propulsive integral was determined as the area under this anterior ground reaction force curve. Paretic propulsive integral, a gait variable directly targeted by plantarflexor FES and fast walking, and correlated with hemiparetic severity and gait asymmetry,⁴⁻⁷ was the primary outcome measure for the study. The peak knee flexion angle during the swing phase, also targeted by the FastFES intervention, was the secondary outcome variable used to assess gait performance. The overground gait speed was another secondary outcome used to track the overall change in gait function after 6 weeks of training. These dependent variables were selected to evaluate effects of training on the specific gait impairments targeted by the FastFES intervention.

Measurement of Motor Learning

Using gait analysis data collected during the pre-, post-, and retention tests during the first and sixth training weeks (Figure 1), 2 change scores were computed to evaluate motor learning. Online gains (within-session gains) in gait performance were computed as follows:

$$\text{Online Gain} = [(\text{Posttest}) - (\text{Pretest})] / \text{Pretest}$$

Retention (motor learning) was computed as follows:

$$\text{Retention} = [(\text{Retention Test}) - (\text{Pretest})] / \text{Pretest}$$

Thus, a positive online gain score would indicate a within-session improvement in the gait variable. A positive retention score would indicate an increase in the gait variable between the pretest and retention test. These change scores were used to evaluate the magnitude of motor learning induced by a single training session during the first and sixth weeks. The change scores were converted to a percentage to enable normalized comparisons between the first and sixth training weeks.

OUTCOMES

Improvements in Gait Speed, Paretic Propulsion, and Swing Phase Knee Flexion After 6 Weeks of Gait Training

After 6 weeks of training, the subject showed an increase in overground gait speed from 0.38 m/s (household ambulator)

to 0.57 m/s (limited community ambulator⁴), with a change of 0.19 m/s. This change in speed exceeded the minimal clinically important difference of 0.16 m/s for overground gait speed in stroke.⁴³ The increase in speed was accompanied by improvements in paretic propulsion (55.4% increase) and swing phase knee flexion (25.2% increase) (Figure 2).

Motor Learning Change Scores During the First Training Week

During the first training session of week 1, paretic propulsive integral increased from 1.42 at pretest to 2.22% body weight-seconds at posttest (55.7% increase). During the retention test performed 48 hours after the training session, paretic propulsion was 2.01% body weight-seconds. This is a retention of 41% compared with the pretest (Figures 2 and 3). Likewise, paretic peak swing phase knee flexion increased from 17° at pretest to 23° at posttest (31.5% increase). During the retention test performed 48 hours after the training session, knee flexion was 21°, a retention of 20.3% compared with the pretest (Figures 2 and 3).

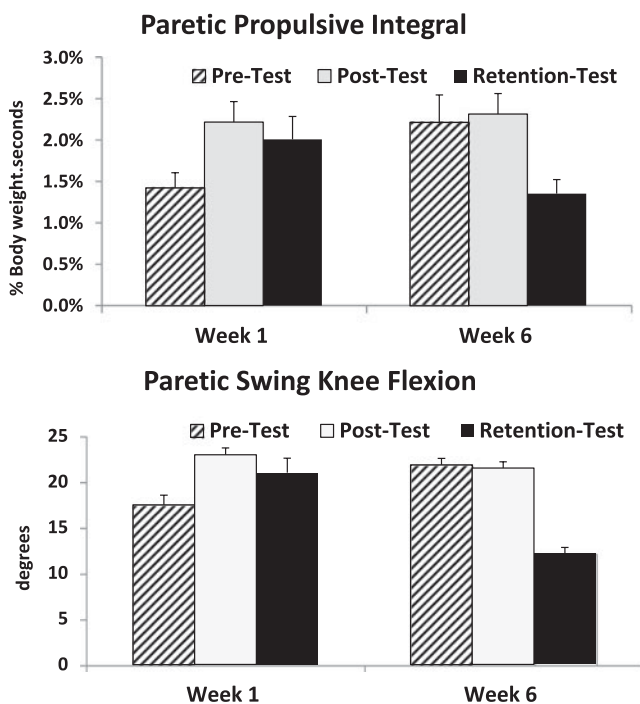


Figure 2. Bar plots showing the values of the biomechanical variables—paretic propulsive integral (top panel) and paretic swing knee flexion (bottom panel) obtained during the pretest, posttest, and retention test conducted during week 1 and week 6 of FastFES gait training. For both variables, greater values indicate improvement. The overall change with 6 weeks of training was computed by comparing the pretest data from week 1 and week 6. Each bar represents an average of 9 gait cycles; error bars represent standard errors across gait cycles.

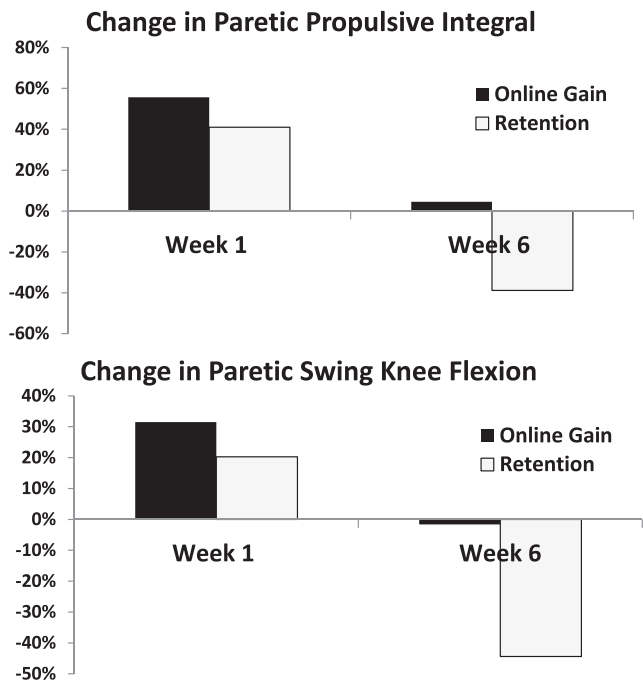


Figure 3. Bar plots showing the change scores used to evaluate motor learning for the 2 biomechanical gait variables (top: paretic propulsive integral; bottom: paretic swing knee flexion) during week 1 and week 6. Online gain refers to the increase in the variable within one training session (pretest to posttest, positive values indicate an increase). Retention, the gold standard for motor learning, refers to the change in the variable from the pretest to the retention test conducted 48 hours after the training session (positive values indicate improvement or motor learning).

Motor Learning During the First Versus the Sixth Training Week

Comparison of change scores for paretic propulsive integral during the first versus the sixth week revealed that the training session in the first week produced greater online gains (55.7% during week 1 vs 4.5% during week 6), and greater motor learning (41% during week 1 vs -38.9% during week 6) during the first versus sixth week of gait training (Figure 3). Similarly for paretic knee flexion, the online gains and retention were greater during week 1 versus week 6 (Figure 3).

DISCUSSION

This case study used the FastFES gait retraining intervention as a paradigm to investigate the magnitude and time course of motor learning during clinical poststroke gait rehabilitation. We hypothesized that if the FastFES gait training session induces motor learning of improved gait patterns, we would observe within-session improvements in the biomechanical variables being targeted, and more importantly, retention of these improvements 48 hours after the training session. Consistent with our hypothesis, during week 1, we showed that paretic propulsive integral and paretic knee flexion improved after a single training session. Furthermore, during the first

week of training, motor learning of targeted gait biomechanics was indicated by retention of improved paretic propulsion and paretic knee flexion 48 hours after the training session. Interestingly, we also showed that the magnitude of motor learning was greater during the first versus the sixth training week, suggesting that these motor learning change scores may differ markedly during the early versus late stages of gait rehabilitation. To our knowledge, this is the first report evaluating motor learning (using within-session changes in gait performance and retention of gait performance at the next training session) during the course of a clinical gait rehabilitation training session. Our findings regarding the differences in magnitude of motor learning during week 1 versus week 6 are also novel and merit investigation in a group study design.

In this case study, we conducted a systematic evaluation of the within- and across-session changes in the poststroke gait variables targeted by the intervention to evaluate motor learning during FastFES training. The change scores used here (online gains, retention) are inspired by the motor learning literature.⁴⁴ Motor learning studies typically capitalize on controlled experimental motor tasks such as reaching or stepping movements often performed against a force field.^{21,23,31,44} Motor learning likely evolves over 2 time scales: a fast component that occurs within a training session and a delayed latent component that occurs after the training session.^{44,45} The within-session improvements or online gains observed in our current study may be the product of these fast processes occurring as the stroke survivors relearned new gait patterns during the training session. Although improvements in the targeted performance variable within the training session (online gains) demonstrate motor skill acquisition and are important, alone, they do not suggest the presence of motor learning. Consolidation is a set of processes whereby a long-term memory becomes more stable with the passage of time.^{44,46} Consolidation of learning, thought to be influenced by both time and sleep, is demonstrated by *persistence* of the within-session performance improvements after a delay period (ie, retention). In our case study, retention was assessed by comparing the paretic propulsion and knee flexion during the retention test conducted 48 hours after the training session with the pretest conducted at the beginning of the training session. The fact that we showed positive retention scores (41% for paretic propulsion and 20.3% for paretic knee flexion) during week 1 provides evidence that the FastFES training program promoted the learning of biomechanical gait parameters targeted by training.

To our knowledge, differences in motor learning between early (here the first week) and later stages (sixth week) of gait training have not previously been reported and merit further investigation. Our comparisons of retention during week 1 and week 6 suggest that the capacity for motor learning may be greater during the earlier stages of a gait intervention, perhaps because the training program is “novel” and more challenging for the subject at that time. After repeated exposure to the same training paradigm over multiple training sessions (ie, during week 6), the training regimen may not be sufficiently challenging to induce motor learning. Negative retention during week 6 (ie, a marked decrement in gait performance at the retention test compared with the beginning of the training session) was an unexpected finding. Here, we were unable to

control the amount and type of walking practice the subject engaged in during the period between the training and the retention test, as is common during clinical gait rehabilitation. The negative retention observed during week 6 may reflect session-to-session gait variability, or be a finding specific to this case study subject, but merits investigation in future studies. The change scores used to assess motor learning during weeks 1 and 6 were measured over a 48-hour period and normalized to the pretest data for each week, thus enabling a measurement of online gains and retention induced by a single training session. It is also important to note that these negative retention change scores during week 6 were observed *despite* the overall improvement in gait speed, propulsion, and knee flexion during week 6 versus week 1. Also, the pre-, post-, and retention test data were collected at the subject's initial self-selected speed (determined during the first week) although his self-selected speed increased from the first to sixth weeks. It is possible that the negative retention scores observed during week 6 were caused by the subject being tested at a speed that was slower than his current comfortable speed. However, we computed the within-session and retention change scores for week 6 using gait analysis tests conducted at the new, faster self-selected speed from week 6, and found the similar trends as reported here. It is also conceivable that by the sixth training week, the improvements in gait speed, gait biomechanics, and thereby balance confidence produced by the intervention equipped the subject with novel biomechanical strategies and gait compensations that enabled improvements in gait speed without necessitating concomitant within- and across-session improvements in specific paretic limb impairments. During gait rehabilitation, assessment of gait biomechanics along with measurement of gait function, activity, and participation may help elucidate the interplay between restoration of gait impairments and development of new gait compensations as a gait retraining program evolves. Rehabilitation studies typically assess gait function before and after 6 or 12 weeks of training; within- and across-session changes in gait performance are not usually reported. The findings of this case study demonstrate the need to study the time courses of within- and across-session changes, as well as factors influencing the capacity for motor learning, during poststroke gait rehabilitation.

The innovation of this case report is the systematic evaluation of within- and across-session changes to assess motor learning during clinical poststroke gait rehabilitation. Conclusions from this case study are limited to a single individual. Our current case report provides interesting and innovative findings and strongly supports the need for systematically evaluating motor learning mechanisms and time courses in larger scale studies. Conclusions are further limited by the fact that the individual studied was 15.5 months poststroke. The effects of initiating therapy during the first few days and weeks after stroke on motor learning and time course of gait improvements are important questions that deserve investigation in future studies. After 6 weeks of training, the study subject showed an increase in gait speed of 0.19 m/s, a change larger than the minimal clinically important difference for walking speed poststroke (0.16 m/s).⁴³ Despite this change, the individual still had gait disability, highlighting the need to improve the effectiveness of gait training and enable the subject to

make even greater gains in walking speed and transition from a household ambulatory to a community ambulator.⁴⁷ During the intervention in this case study, no explicit feedback was provided about errors or deviation from the targeted task. The physical therapist's verbal instructions to the subject were standardized to prevent differences in response to treatment because of the type of feedback. During training, no tactile cues were provided by the physical therapist. Although this helped make the training protocol standardized and replicable, individualized verbal and tactile cues may be valuable for promoting learning and retention.

The purpose of this case study was to explore the magnitude and time course of motor learning during clinical post-stroke gait rehabilitation. We postulate that an in-depth understanding of the magnitude and time course of motor learning during gait retraining can help maximize the effects of each session and each week of rehabilitation. We demonstrate the advantage of using within- and across-session changes for systematically tracking motor learning during clinical gait rehabilitation. In the context of motor learning, the goal of each physical therapy treatment session may be to induce a positive within-session change or online gains, and achieve positive retention (ie, greater performance at the start of the second vs the first treatment session). Other strategies such as verbal feedback about gait performance, which was shown to be effective at improving gait speed in a randomized controlled trial, may be used to enhance motor learning during clinical gait rehabilitation.⁴⁸ An in-depth understanding of the motor learning mechanisms during rehabilitation may aid in the design of more effective and more individualized schedules for gait retraining and development of novel strategies to promote motor learning during gait rehabilitation.

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REFERENCES

- Granger CV, Hamilton BB, Gresham GE. The stroke rehabilitation outcome study—Part I: general description. *Arch Phys Med Rehabil.* 1988;69(7):506-509.
- Chen G, Patten C, Kothari DH, Zajac FE. Gait differences between individuals with post-stroke hemiparesis and non-disabled controls at matched speeds. *Gait Posture.* 2005;22(1):51-56.
- Olney SJ, Richards C. Hemiparetic gait following stroke. Part I: characteristics. *Gait Posture.* 1996;4:136-148.
- Bowden MG, Balasubramanian CK, Behrman AL, Kautz SA. Validation of a speed-based classification system using quantitative measures of walking performance poststroke. *Neurorehabil Neural Repair.* 2008;22(6):672-675.
- Bowden MG, Balasubramanian CK, Neptune RR, Kautz SA. Anterior-posterior ground reaction forces as a measure of paretic leg contribution in hemiparetic walking. *Stroke.* 2006;37(3):872-876.
- Balasubramanian CK, Bowden MG, Neptune RR, Kautz SA. Relationship between step length asymmetry and walking performance in subjects with chronic hemiparesis. *Arch Phys Med Rehabil.* 2007;88(1):43-49.
- Peterson CL, Hall AL, Kautz SA, Neptune RR. Pre-swing deficits in forward propulsion, swing initiation and power generation by individual muscles during hemiparetic walking. *J Biomech.* 2010;43(12):2348-2355.
- Dickstein R. Rehabilitation of gait speed after stroke: a critical review of intervention approaches. *Neurorehabil Neural Rep.* 2008;22(6):649-660.
- Robbins SM, Houghton PE, Woodbury MG, Brown JL. The therapeutic effect of functional and transcutaneous electric stimulation on improving gait speed in stroke patients: a meta-analysis. *Arch Phys Med Rehabil.* 2006;87(6):853-859.
- Dobkin BH. Motor rehabilitation after stroke, traumatic brain, and spinal cord injury: common denominators within recent clinical trials. *Curr Opin Neurol.* 2009;22(6):563-569.
- Dobkin BH. Confounders in rehabilitation trials of task-oriented training: lessons from the designs of the EXCITE and SCILT multicenter trials. *Neurorehabil Neural Rep.* 2007;21(1):3-13.
- Sullivan KJ, Knowlton BJ, Dobkin BH. Step training with body weight support: effect of treadmill speed and practice paradigms on poststroke locomotor recovery. *Arch Phys Med Rehabil.* 2002;83(5):683-691.
- Silver KH, Macko RF, Forrester LW, Goldberg AP, Smith GV. Effects of aerobic treadmill training on gait velocity, cadence, and gait symmetry in chronic hemiparetic stroke: a preliminary report. *Neurorehabil Neural Rep.* 2000;14(1):65-71.
- Menon A, Korner-Bitensky N, Kastner M, McKibbin KA, Straus S. Strategies for rehabilitation professionals to move evidence-based knowledge into practice: a systematic review. *J Rehabil Med.* 2009;41(13):1024-1032.
- Daly JJ, Roenigk K, Holcomb J, et al. A randomized controlled trial of functional neuromuscular stimulation in chronic stroke subjects. *Stroke.* 2006;37(1):172-178.
- Visintin M, Barbeau H, Korner-Bitensky N, Mayo NE. A new approach to retrain gait in stroke patients through body weight support and treadmill stimulation. *Stroke.* 1998;29(6):1122-1128.
- Pohl M, Mehrholz J, Ritschel C, Ruckriem S. Speed-dependent treadmill training in ambulatory hemiparetic stroke patients: a randomized controlled trial. *Stroke.* 2002;33(2):553-558.
- Tucker JA, Reed GM. Evidentiary pluralism as a strategy for research and evidence-based practice in rehabilitation psychology. *Rehabil Psychol.* 2008;53(3):279-293.
- Concato J, Shah N, Horwitz RI. Randomized, controlled trials, observational studies, and the hierarchy of research designs. *New Eng J Med.* 2000;342(25):1887-1892.
- Schmidt RA. *Motor Control and Learning.* 2nd ed. Champaign, IL: Human Kinetics Publishers; 1988.
- Krakauer JW. Motor learning: its relevance to stroke recovery and neurorehabilitation. *Curr Opin Neurol.* 2006;19(1):84-90.
- Hanlon RE. Motor learning following unilateral stroke. *Arch Phys Med Rehabil.* 1996;77(8):811-815.
- Halsband U, Lange RK. Motor learning in man: a review of functional and clinical studies. *J Physiol Paris.* 2006;99(4-6):414-424.
- Bastian AJ. Understanding sensorimotor adaptation and learning for rehabilitation. *Curr Opin Neurol.* 2008;21:628-633.
- Boyd L, Winstein C. Explicit information interferes with implicit motor learning of both continuous and discrete movement tasks after stroke. *J Neurol Phys Ther.* 2006;30(2):46-57; discussion 58-49.
- Cirstea MC, Levin MF. Improvement of arm movement patterns and endpoint control depends on type of feedback during practice in stroke survivors. *Neurorehabil Neural Rep.* 2007;21(5):398-411.
- van Vliet PM, Wulf G. Extrinsic feedback for motor learning after stroke: what is the evidence? *Disabil Rehabil.* 2006;28(13-14):831-840.
- Boyd LA, Quaney BM, Pohl PS, Winstein CJ. Learning implicitly: effects of task and severity after stroke. *Neurorehabil Neural Rep.* 2007;21(5):444-454.
- Boyd LA, Winstein CJ. Implicit motor-sequence learning in humans following unilateral stroke: the impact of practice and explicit knowledge. *Neurosci Lett.* 2001;298(1):65-69.
- Boyd LA, Winstein CJ. Impact of explicit information on implicit motor-sequence learning following middle cerebral artery stroke. *Phys Ther.* 2003;83(11):976-989.
- Winstein CJ, Merians AS, Sullivan KJ. Motor learning after unilateral brain damage. *Neuropsychologia.* 1999;37(8):975-987.
- Kesar TM, Perumal R, Jancosko A, et al. Novel patterns of functional electrical stimulation have an immediate effect on dorsiflexor muscle function during gait for people poststroke. *Phys Ther.* 2010;90(1):55-66.
- Kesar TM, Perumal R, Reisman DS, et al. Functional electrical stimulation of ankle plantarflexor and dorsiflexor muscles: effects on poststroke gait. *Stroke.* 2009;40(12):3821-3827.
- Kesar TM, Reisman DS, Perumal R, et al. Combined effects of fast treadmill walking and functional electrical stimulation on post-stroke gait. *Gait Posture.* 2011;33(2):309-313.

35. Krishnamoorthy V, Hsu WL, Kesar TM, et al. Gait training after stroke: a pilot study combining a gravity-balanced orthosis, functional electrical stimulation, and visual feedback. *J Neurol Phys Ther.* 2008;32(4):192-202.
36. Perumal R, Kesar TM, Wexler AS, Binder-Macleod SA. Novel FES system to stimulate both dorsi- and plantar-flexor muscles during stroke gait. Paper presented at 12th Annual Conference of the International FES Society 2007; Philadelphia, PA.
37. Hakansson NA, Kesar T, Reisman D, Binder-Macleod S, Higginson JS. Effects of fast functional electrical stimulation gait training on mechanical recovery in poststroke gait. *Artif Organs.* 2011;35(3):217-220.
38. Kesar TM, Reisman RS, Roos M, Perumal R, Farquhar W, Binder-Macleod SA. Novel Locomotor Training Improves Gait Performance, Activity, and Participation in Individuals with Chronic Stroke. Paper presented at Combined Sections Meeting, American Physical Therapy Association 2011; New Orleans, LA.
39. Reisman D, Kesar T, Perumal R, et al. Time course of functional and biomechanical improvements during a gait training intervention in persons with chronic stroke. *J Neurol Phys Ther.* 2013;37(4):159-165.
40. Nudo RJ, Plautz EJ, Frost SB. Role of adaptive plasticity in recovery of function after damage to motor cortex. *Muscle Nerve.* 2001;24(8):1000-1019.
41. Shumway-Cook A, Brauer S, Woollacott M. Predicting the probability for falls in community-dwelling older adults using the Timed Up & Go Test. *Phys Ther.* 2000;80(9):896-903.
42. Kesar TM, Binder-Macleod SA, Hicks GE, Reisman DS. Minimal detectable change for gait variables collected during treadmill walking in individuals post-stroke. *Gait Posture.* 2011;33(2):314-317.
43. Tilson JK, Sullivan KJ, Cen SY, et al. Meaningful gait speed improvement during the first 60 days poststroke: minimal clinically important difference. *Phys Ther.* 2010;90(2):196-208.
44. Krakauer JW, Shadmehr R. Consolidation of motor memory. *Trends Neurosci.* 2006;29(1):58-64.
45. Karni A, Meyer G, Rey-Hipolito C, et al. The acquisition of skilled motor performance: fast and slow experience-driven changes in primary motor cortex. *Proc Nat Acad Sci U S A.* 1998;95(3):861-868.
46. Dudai Y. The neurobiology of consolidations, or, how stable is the engram? *Annu Rev Psychol.* 2004;55:51-86.
47. Schmid A, Duncan PW, Studenski S, et al. Improvements in speed-based gait classifications are meaningful. *Stroke.* 2007;38(7):2096-2100.
48. Dobkin BH, Plummer-D'Amato P, Elashoff R, Lee J. International randomized clinical trial, Stroke Inpatient Rehabilitation With Reinforcement of Walking Speed (SIRROWS), improves outcomes. *Neurorehab Neural Rep.* 2010;24(3):235-242.

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