Overground Locomotor Training in Spinal Cord Injury: A Performance-Based Framework

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Background: Locomotor training (LT) is the most commonly used treatment to improve walking performance following spinal cord injury (SCI). The advancement of LT treatments requires the addition of integrative models accounting for the numerous systems responsible for the recovery of walking function following SCI. **Objective:** This perspective monograph aims to (a) describe a performance-based framework for overground LT (OLT), (b) describe principles of adaptation and motor learning used to inform OLT program design, and (c) present an example OLT program based on the proposed framework. **Methods:** Individuals with chronic motor-incomplete SCI (7 male, 1 female) classified according to the American Spinal Injury Association Impairment Scale (AIS) as C and D were included. OLT included two 90-minute sessions performed over 12 weeks for a total of 24 sessions. Outcomes measures included overground walking speed, walking economy, pulmonary oxygen uptake, and muscle oxygen extraction measured via near-infrared spectroscopy. **Results:** Preliminary findings demonstrate the potential of OLT, as describe here, to increase overground walking speed, improve walking economy, accelerate processes associated with oxygen delivery and utilization at the rest-to-work transition, and lower oxygen extraction requirements of skeletal muscle during walking in individuals with chronic motor-incomplete SCI. **Conclusion:** The proposed framework offers a valuable template for LT program design in both clinical and research settings. Further research is necessary to better understand the effects of OLT and how principles of specificity, progressive overload, and variation within the performance-based framework can be manipulated to maximize function, health, and quality of life in SCI. **Key words:** exercise, locomotion, rehabilitation, spinal cord injuries

Incomplete spinal cord injury (SCI) results in partial preservation of the sensory and/or motor function below the level of the lesion.¹ Given that some neurological function is maintained, individuals with incomplete SCI have demonstrated the potential of regaining ambulatory capabilities.^{2,3} Locomotor training (LT) is the most commonly used treatment to improve walking performance following SCI. LT comprises any training method aiming to improve walking using a variety of modalities either independently or in combination.⁴ Currently available approaches are often based solely on theories of motor learning and neuroplasticity.⁴⁻⁸ However, the advancement of LT treatments requires the addition of integrative models accounting for the numerous systems responsible for the recovery of walking function following SCI.

Extensive frameworks detailing the conceptual basis and program elements for LT programs specific to overground training are currently lacking. The purpose of this perspective monograph is to (a) describe a performance-based framework for overground LT (OLT), (b) provide an overview of specific principles of adaptation and motor learning used to inform OLT program design, and (c) present an example OLT program based on the proposed framework. Although a comprehensive review of all concepts is beyond the scope of this article, our intention is to outline the proposed framework integrating the understanding of rehabilitation science, exercise physiology, motor control, and motor learning to assist others in the design of future LT programs. To highlight practical implications of this approach, pilot data obtained from 8 people with chronic motor-incomplete SCI are provided.

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Performance-based Framework

An individual's walking performance emerges as the resolution of the interactions of specific constraints to achieve a desired movement.^{9,10} Newell⁹ identified 3 loci of constraints—organismic, environment, and task – and described them as boundaries limiting motion of the entity under consideration. Organismic constraints reside within the organism and include constraints at the structural and functional levels operating over varying timescales.¹¹ For example, the constraint of self-efficacy may operate over a shorter timescale compared to cardiorespiratory adaptations if self-efficacy is improved early in the training cycle. Environmental constraints are viewed as any constraint on the organism-environment interaction not internal to the organism, and they

include assistive devices, body-weight support, and robotics.¹¹ Task constraints describe the goal of the task and rules specifying or constraining response dynamics.⁹

We have extended the original model proposed by Newell⁹ and adapted by Davids et al¹⁰ to further consider the impact of principles of adaptation and motor learning on both constraints and performance (Figure 1) specific to overground walking after chronic motor-incomplete SCI. Improvements in performance may occur through explicit modifications of constraints or direct modulation of constraint interactions to meet the demands of goal-directed activity more appropriately. Similarly, experience and deliberate practice of the activity itself may also lead to improved performance resulting from

Figure 1. Newell's model of interacting constraints adapted to illustrate the resulting effects on variability of physical performance.¹⁰ We have further adapted the model to describe a performance-based framework and the potential impact of overground locomotor training (OLT) following spinal cord injury (SCI) on both constraints and performance. Adapted with permission from Davids K, Glazier P, Araújo D, Bartlett R. Movement systems as dynamical systems: The functional role of variability and its implications for sports medicine. *Sports Med Auckl NZ*. 2003;33(4):245-260. Copyright © 2003 Springer.

more appropriate constraint interactions to meet the demands of the activity without any direct modifications to individual constraints themselves.¹²

We propose that recovery of function cannot be evaluated outside of the context of constraint interactions for the optimization of “movement solutions.” From a performance perspective, there are multiple equivalent “solutions,” but some are more successful than others with respect to managing the trade-offs between energy expenditure and mechanical efficiency.¹³ Performance-based approaches evaluate and respond to how individuals manage various types of constraints to achieve goal-directed actions, tasks, and activities under real-world conditions. Such a framework attempts to account for adaptation in the physiological sense as well as motor learning and thus captures their potential synergy, which is facilitated by applying the principles of specificity, overload, and variation. In contrast to impairment-based frameworks that emphasize remediation of underlying impairments with the hope of translating to improved function, performance-based approaches consider impairments only to the extent that they contribute to understanding how the individual is able to resolve constraints in achieving the desired performance.

Principles of Adaptation and Motor Learning

Specificity

Specificity refers to the similarities between training stimulus and performance of interest.¹⁴ These points of comparison may include biomechanical, bioenergetic, and informational demands of activity and can occur at the molecular and cellular, organ and organ system, or whole body levels.¹⁵ The importance of task specificity has been demonstrated in animals and humans with SCI.^{7,16-20} For example, when comparing stepping training to standing training in spinalized cats, it was demonstrated that recovery of stepping capabilities occurred only after stepping training.¹⁷ Similarly, specificity of sensory feedback is suggested to be a critical component for promoting neuroplasticity in humans.²¹ Specificity of training

environment has also been shown to result in differences in overground walking outcomes in humans and animals with incomplete SCI.^{7,20} Thus, it is not just specificity of the task but rather specificity of the interactions of the individual, task, and environment that must be considered for LT after SCI.

Progressive overload

Progressive overload describes progressive increases in training stimulus across the training period.²² This is accomplished by increasing frequency (eg, number of days), intensity, volume (eg, repetition), time (eg, number of hours), or movement complexity independently or in combination. Additional strategies include changing the training environment and modifying the rest intervals. The objective of progressive overload is to allow for sufficient exposure to the applied stimuli to promote adaptation while minimizing fatigue.¹⁵ Furthermore, progressive loading attempts to prevent stagnation and promote continued adaptation over longer training periods. Frequency, intensity, volume, time, and environment have been identified as essential variables for LT after SCI.^{3,7,20,21,23} The rate of progression will likely differ depending on the constraints associated with the individual, task, environment, and training goal. Although there are models describing progression across training environments, there is limited evidence regarding the progression of other training variables for LT.^{3,5,24,25}

Variation

Variation describes sequenced manipulations of exercises and training stimuli (eg, volume, intensity, frequency, movement patterns, training environments).²⁶⁻²⁹ Variation is implicated as an essential principle for adaptation and motor learning.^{28,29} Variation as it pertains to adaptation refers to altering exercise selection, volume, or intensity at specified times during training.²⁹ Variation within the context of motor learning, also referred to as *practice variability*, describes structured or unstructured variation in the multiplicity of actions or tasks specific to the

activity of interest during deliberate practice.²⁸ This type of practice can be contrasted with constant practice in which only a particular action, task, or activity is practiced in its entirety in a single environment.¹⁴ Therefore, variation in deliberate practice can be used to allow for exploration in motor patterns to identify the most optimal solutions for performance.²⁸ Among the 3 principles described presently, the extent to which practice variation has been studied is limited within the context of LT following SCI in humans. However, in an SCI animal model, greater improvements in stepping outcomes were observed when animals were trained using variations in stepping patterns (ie, sideways and backwards) compared to forward stepping alone.³⁰

Practice Structure and Organization

Deliberate practice emphasizes highly structured activities based on a specific task with the explicit goal of improving performance.¹² Two commonly used practice paradigms include part practice and whole practice.¹⁴ *Part practice* refers to the deconstruction of the activity of interest into relevant actions and tasks to be practiced in isolation, whereas *whole practice* is the practicing of an activity in its entirety.¹⁴ One benefit of part practice is the associated reductions in cognitive demand when learning complex movements.^{14,31} To account for concerns of transfer of skills from part practice to activity performance, part and whole practice are used sequentially within the same practice session (ie, part to whole practice).^{14,32}

Overground Locomotor Training Program

Guided by the proposed framework, we developed an OLT program with the specific goal of improving overground walking following chronic motor-incomplete SCI. The program includes 24 sessions completed over 12 weeks on nonconsecutive days. Each training session is structured to last no longer than 90 minutes. The segments used to organize each training session and the sequence of movement patterns are standardized, but individualization is accounted for through the use of mobility aids and individualized rate of progression (ie, progressive

overload). Moreover, individualization of the OLT framework can be achieved during segments of joint mobility and volitional neuromuscular activation as described below.

Training phases

The training period consists of 3 phases, each lasting 4 weeks. The training stimulus is progressed when transitioning between phases in accordance to the progressive overload principle. Weekly training sessions are organized into 2 movement categories according to the principle of variation: (1) unidirectional (ie, linear gait mechanics) and (2) multidirectional (ie, directional stepping mechanics). Unidirectional movement patterns are further broken down into stance phase and swing phase, which alternate weekly. Multidirectional movement patterns include lateral, cross-over, backward, and rotational stepping, which also alternate weekly. **Table 1** outlines an example of unidirectional and multidirectional training sessions progressed over the training cycle.

Training sessions

Training sessions are broken down into 5 segments that are performed sequentially. These segments include (1) joint mobility, (2) volitional neuromuscular activation, (3) task isolation, (4) task integration, and (5) activity rehearsal. Together, segments 1 and 2 typically last 15 to 30 minutes and function as preparatory for the following segments. Exercises for these segments are based on the primary impairments impeding walking performance identified by the rehabilitation team during the initial evaluation. Organismic constraints presented in **Figure 1** highlight the most common impairments observed across all participants.

Segments of task isolation, task integration, and activity rehearsal are organized according to part to whole practice.^{14,32} During task isolation and task integration, movement exercises are deconstructed into relevant actions and tasks specific to the movement emphasis of that day (see **Table 1**). For example, during a unidirectional session with a swing phase focus, the task isolation drills may consist of exercises emphasizing pre-swing, initial

Table 1. Modified examples of unidirectional and multidirectional overground locomotor training (OLT) sessions

<i>Movement emphasis: Unidirectional</i>				
<i>Movement focus: Swing phase (pre-swing)</i>				
		Phase I	Phase II	Phase III
Segment	Exercise	Sets x Repetitions	Sets x Repetitions	Sets x Repetitions
Joint mobility	Passive hamstring stretch	1 x 3 x 30 second hold	1 x 3 x 30 second hold	1 x 3 x 30 second hold
Volitional neuromuscular activation	Supine active hip mobility	1 x 5 each leg/each direction	1 x 5 each leg/each direction	1 x 5 each leg/each direction
	Hip flexion	3 x 10 each leg No resistance	3 x 10 each leg Manual resistance	3 x 10 each leg Band resistance
	Side lying hip abduction	3 x 10 each leg No resistance	3 x 10 each leg Manual resistance	3 x 10 each leg Band resistance
Task isolation	Weight shifts	3 x 10 Forearm crutch support Even stance Mediolateral	3 x 10 Forearm crutch support Staggered stance Anteroposterior	3 x 10 Minimal partner support Staggered stance Anteroposterior
Task integration	Small stepping	3 x 10 meters Double forearm crutch Supported	3 x 10 meters Partner supported	3 x 10 meters Minimal to no partner Supported
Activity rehearsal	Walking	3 x 10 meters Double forearm crutch Supported	3 x 15 meters Partner supported	3 x 20 meters Minimal to no partner support
<i>Movement emphasis: Multidirectional</i>				
<i>Movement focus: Backward stepping</i>				
		Phase I	Phase II	Phase III
Segment	Exercise	Sets x Repetitions	Sets x Repetitions	Sets x Repetitions
Joint mobility	Passive hip flexor stretch	1 x 3 x 30 second hold	1 x 3 x 30 second hold	1 x 3 x 30 second hold
Volitional neuromuscular activation	Supine active hip mobility	1 x 5 each leg/each direction	1 x 5 each leg/each direction	1 x 5 each leg/each direction
	Glute bridge	3 x 5 each leg	3 x 10 each leg	3 x 10 each leg with 5 second hold
	Side lying hip abduction	3 x 10 each leg No resistance	3 x 10 each leg Manual resistance	3 x 10 each leg Band resistance
Task isolation	Weight shifts	3 x 10 Forearm crutch support Even stance Mediolateral	3 x 10 Partner support Even stance to knee lift Mediolateral	3 x 10 Minimal partner support Even stance to knee lift w/ single leg balance Mediolateral
Task integration	Backward stepping to even stance (non-alternating)	3 x 10 meters Double forearm crutch Supported	3 x 10 meters Partner supported	3 x 10 meters Minimal to no partner support
Activity rehearsal	Backward walking	3 x 10 meters Double forearm crutch Supported	3 x 15 meters Partner supported	3 x 20 meters Minimal to no partner support

and mid-swing, or terminal-swing while standing in place. These same movement patterns would then be incorporated into exercises that require the individual to be moving forward during task integration. Finally, during activity rehearsal,

the individual practices the activity of forward walking while focusing on the previously practiced movements. Active exploration to arrive at a resolution of constraints and an effective “movement solution” during these segments is emphasized.

These 3 segments combined take approximately 60 minutes to complete, with rest breaks given only as necessary to ensure participant safety.

Preliminary Findings

The practical implications of the proposed framework are highlighted with pilot data collected over the course of 2 years. To provide a comprehensive understanding of the described program, functional, physiological, biomechanical, and psychological variables were assessed.³³⁻³⁶ Baseline measurements included assessments of submaximal cardiopulmonary exercise testing, 10-meter walk test, 6-minute walk test, Berg Balance Scale, Jebsen Hand Function Test, and movement self-confidence questionnaire.^{22,37-40} Inclusion criteria included individuals with chronic motor-incomplete SCI possessing the functional capability of standing from a seated position with minimal assistance from one other person and the ability to volitionally initiate and complete at least one step (males, 7; females, 1; age range, 18-67 years). Of the 8 individuals who completed the entire 24-session OLT program, 7 had cervical level injuries and 1 had a thoracic level injury. The cervical level injuries were the result of a diving accident ($n = 3$), a motor vehicle accident ($n = 2$), a fall ($n = 1$), and a recreational sporting accident ($n = 1$). The thoracic level injury was the result of vascular complications ($n = 1$). All participants are classified according to the American Spinal Injury Association Impairment Scale (AIS) as C ($n = 6$) and D ($n = 2$),⁴¹ and time since injured ranged from 2 to 5 years. Primary mode of community ambulation included wheelchair ($n = 4$), walker ($n = 2$), 4-point cane ($n = 1$), and independent ambulation ($n = 1$). The training program is free of charge, and all participants were given the option to continue training after the completion of their first 24-session cycle. To date no adverse events or drop-outs have been reported, and all participants have re-enrolled into the training program.

Our preliminary data on overground walking speed demonstrate an increase from 0.36 to 0.51 m/s (range: pre, 0.15-0.67 m/s; post, 0.24-0.88 m/s) with all participants improving their walking speed above the calculated minimally

important difference (ie, $MID \geq 0.04$ m/s).⁴² We also observed improvements in treadmill walking economy as reflected by a reduction in oxygen cost for a given walking speed (pre, 6.6 mL/kg/min; post, 5.7 mL/kg/min) with concomitant reductions in carbon dioxide production (pre, 753.1 mL/min; post, 670.7 mL/min).⁴² In addition to improved functional outcomes, positive effects on cardiorespiratory and ventilatory parameters have been seen in our participant population.^{33,34} Our data showed a speeding of phase II of pulmonary oxygen uptake kinetics (pulmonary $\dot{V}O_2$ on-kinetics) from 33 seconds to 25 seconds at the onset of treadmill walking and lower oxygen extraction requirements of the lateral gastrocnemius for a given walking speed (pre, 49%; post, 41%) following training.³³ Phase II pulmonary $\dot{V}O_2$ on-kinetics reflects physiological processes associated with oxygen delivery and utilization at the rest-to-work transition.⁴³ The speeding of $\dot{V}O_2$ on-kinetics may have important implications on fatigability and exercise tolerance in SCI as reported in other populations.⁴⁴ Similarly, our data on changes in skeletal muscle oxygenation during treadmill walking assessed using near-infrared spectroscopy (NIRS) demonstrates the potential for adaptations in skeletal muscle oxidative capacity following the described OLT program.³³ Articles that fully document these outcomes are currently under review or in preparation.

Conclusion

The performance-based framework, which integrates the understanding of rehabilitation science, exercise physiology, motor control, and motor learning, provides guiding principles for the structure and organization of LT. Preliminary data suggest the potential for improved walking performance in chronic motor-incomplete SCI following the application of the proposed framework. Further research is necessary to better understand the effects of OLT and how principles of specificity, progressive overload, and variation can be manipulated to maximize function, health, and quality of life across SCI and recovery spectrums.

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